

# GALCIT Colloquium

## 19 October 2018

# The minimal channel for rough-wall turbulent flows

Michael MacDonald



\*Currently a Postdoctoral Fellow at JPL

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Acknowledgements:

Leon Chan, Daniel Chung, Nicholas Hutchins, Andrew Ooi  
Ricardo García-Mayoral

# Motivation



# Motivation

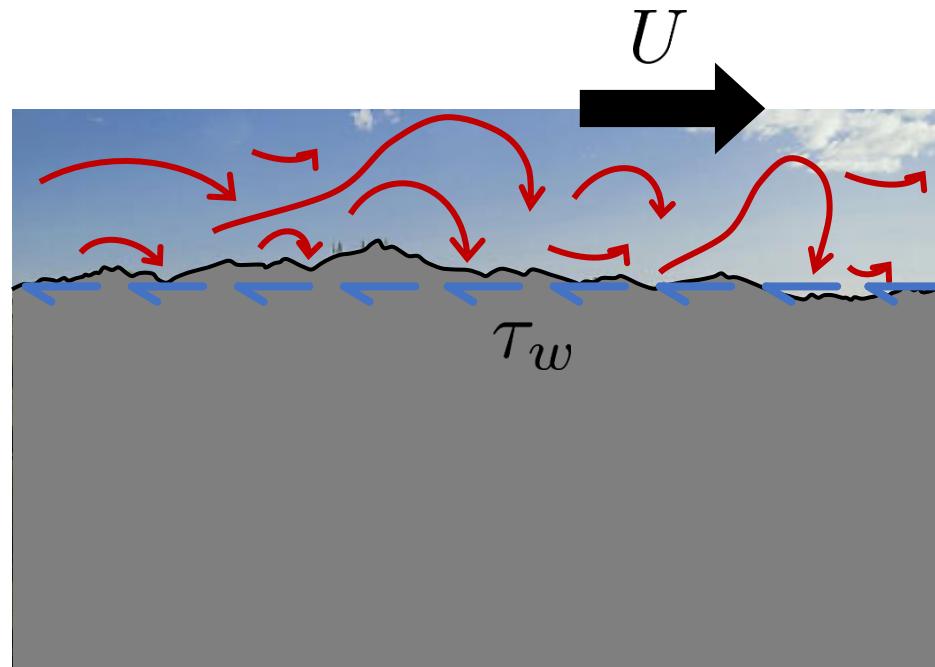


# Motivation

## Roughness size



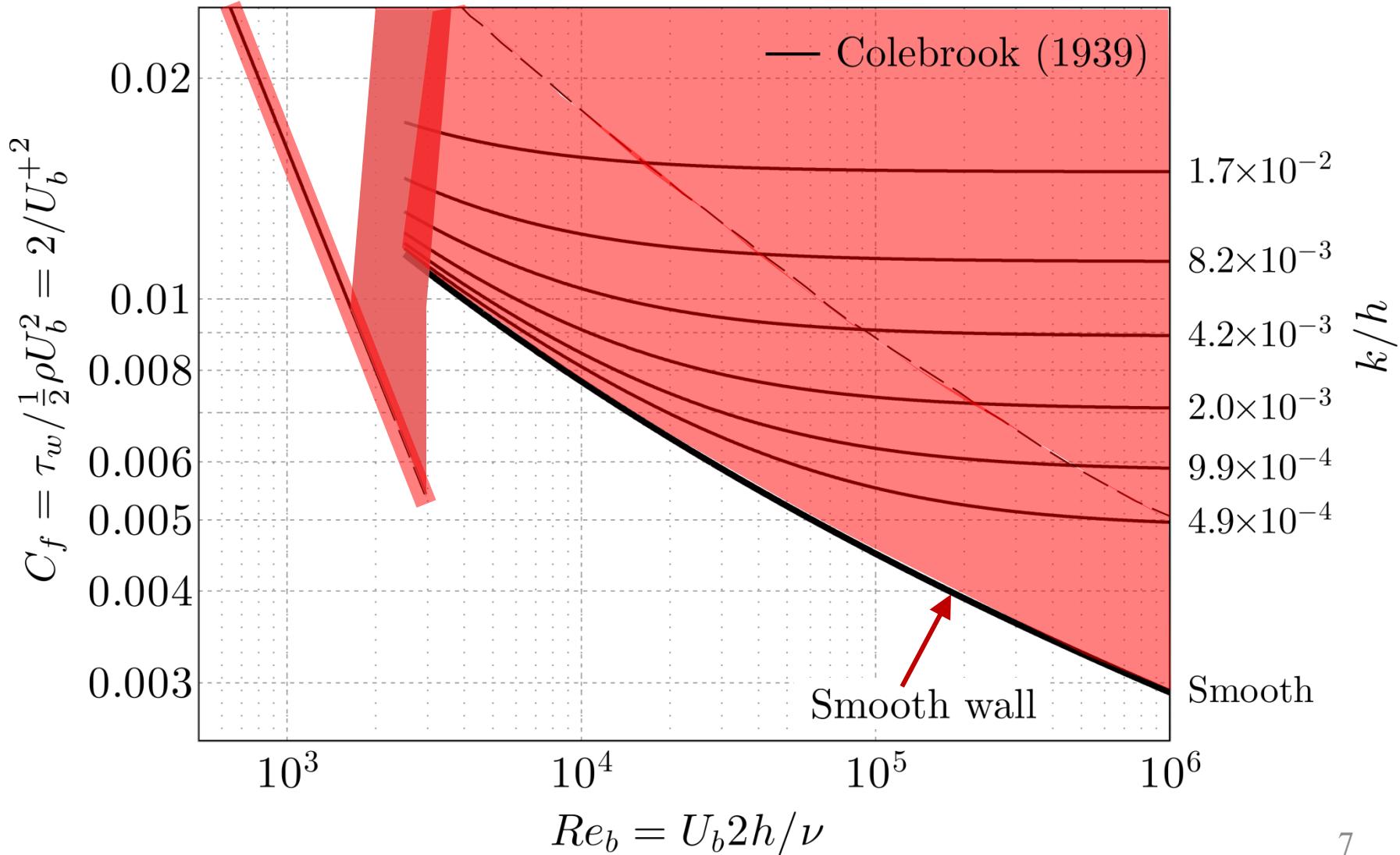
# Motivation



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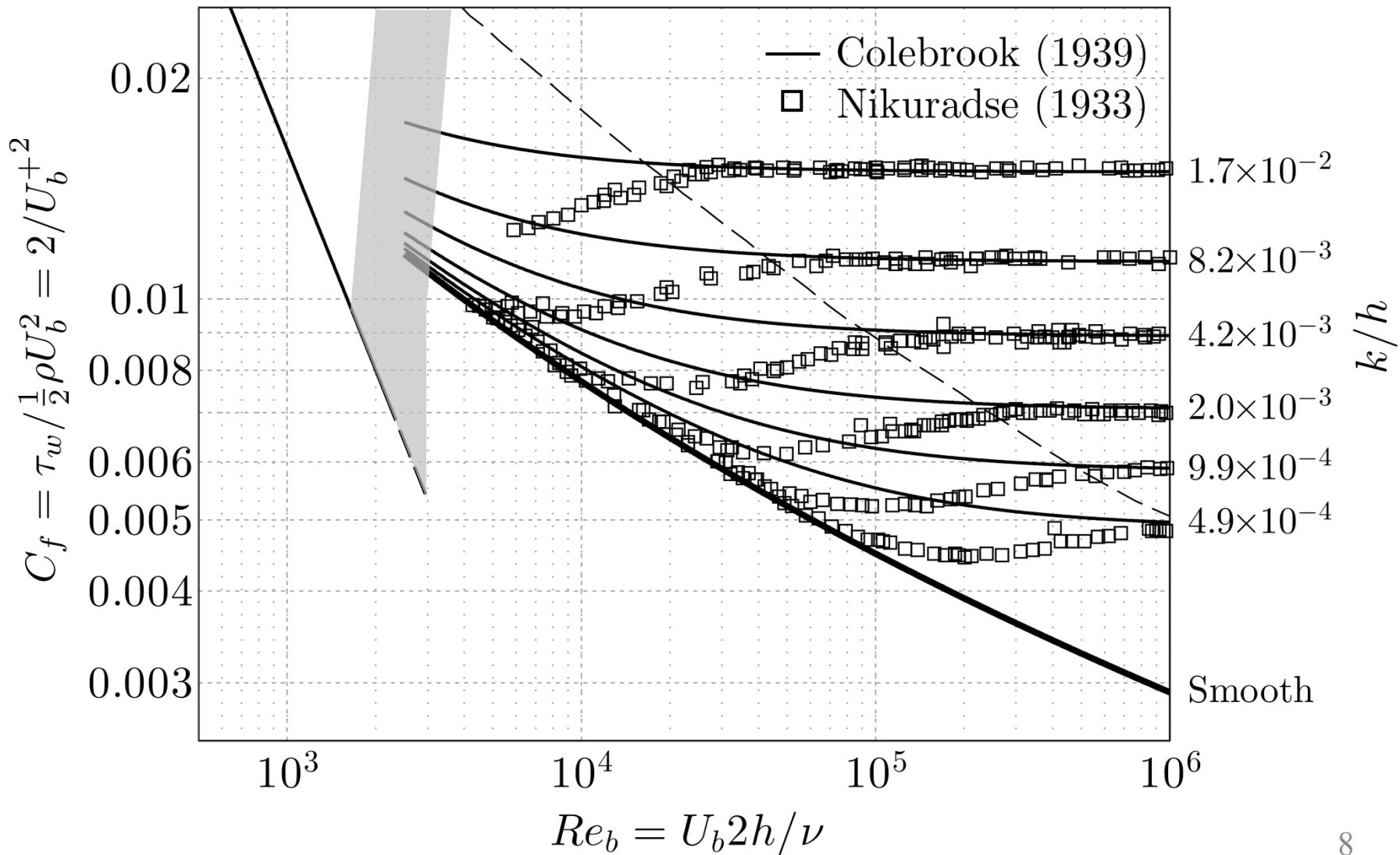
Moody (1944) Chart

Laminar Transition / Re<sub>b</sub> Transitionally rough / Fully rough



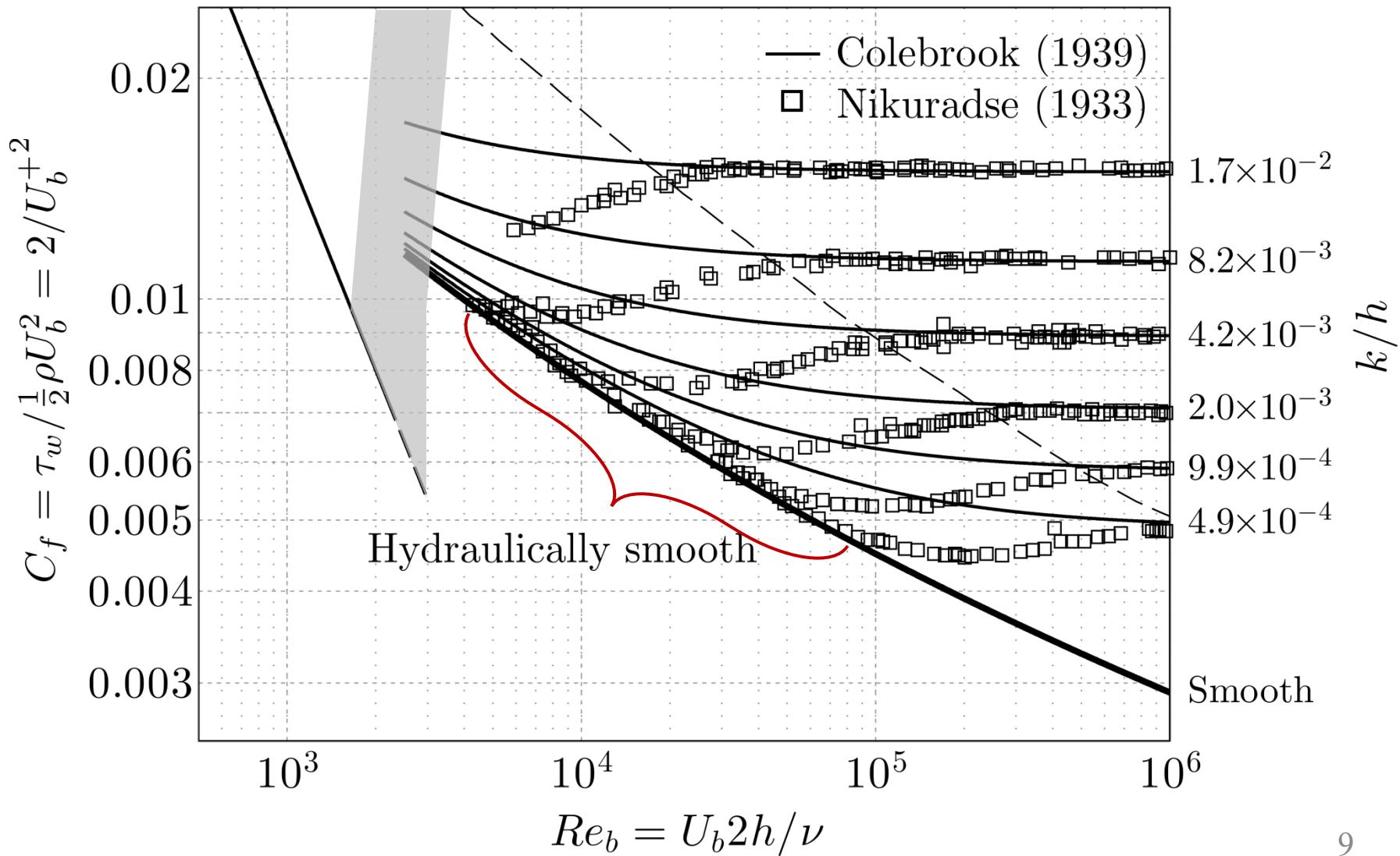
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Moody (1944) Chart



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Moody (1944) Chart

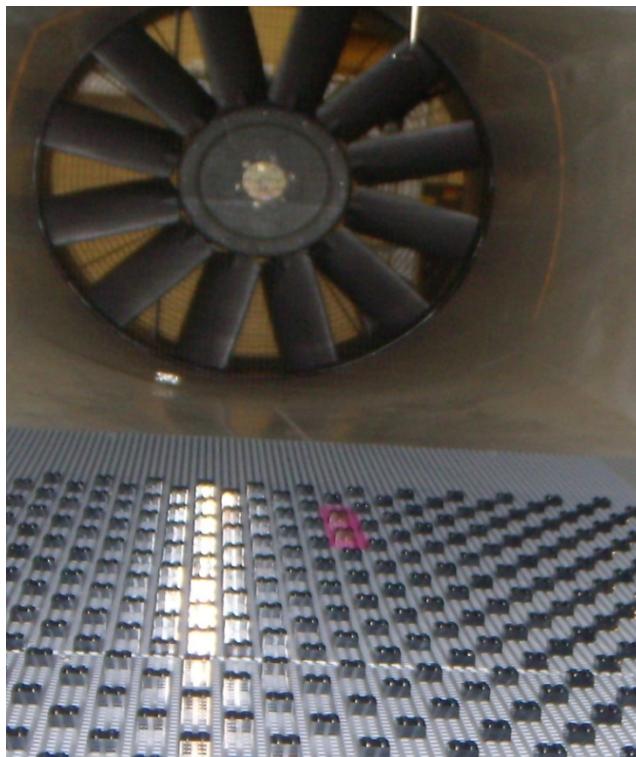


# Motivation

Models to predict  $C_f$  from rough-wall geometry

Involve  $k_{mean}$ ,  $k_{max}$ ,  $k_{rms}$ , skewness, silhouette area...

Direct estimates through laboratory experiments



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Models to predict  $C_f$  from rough-wall geometry

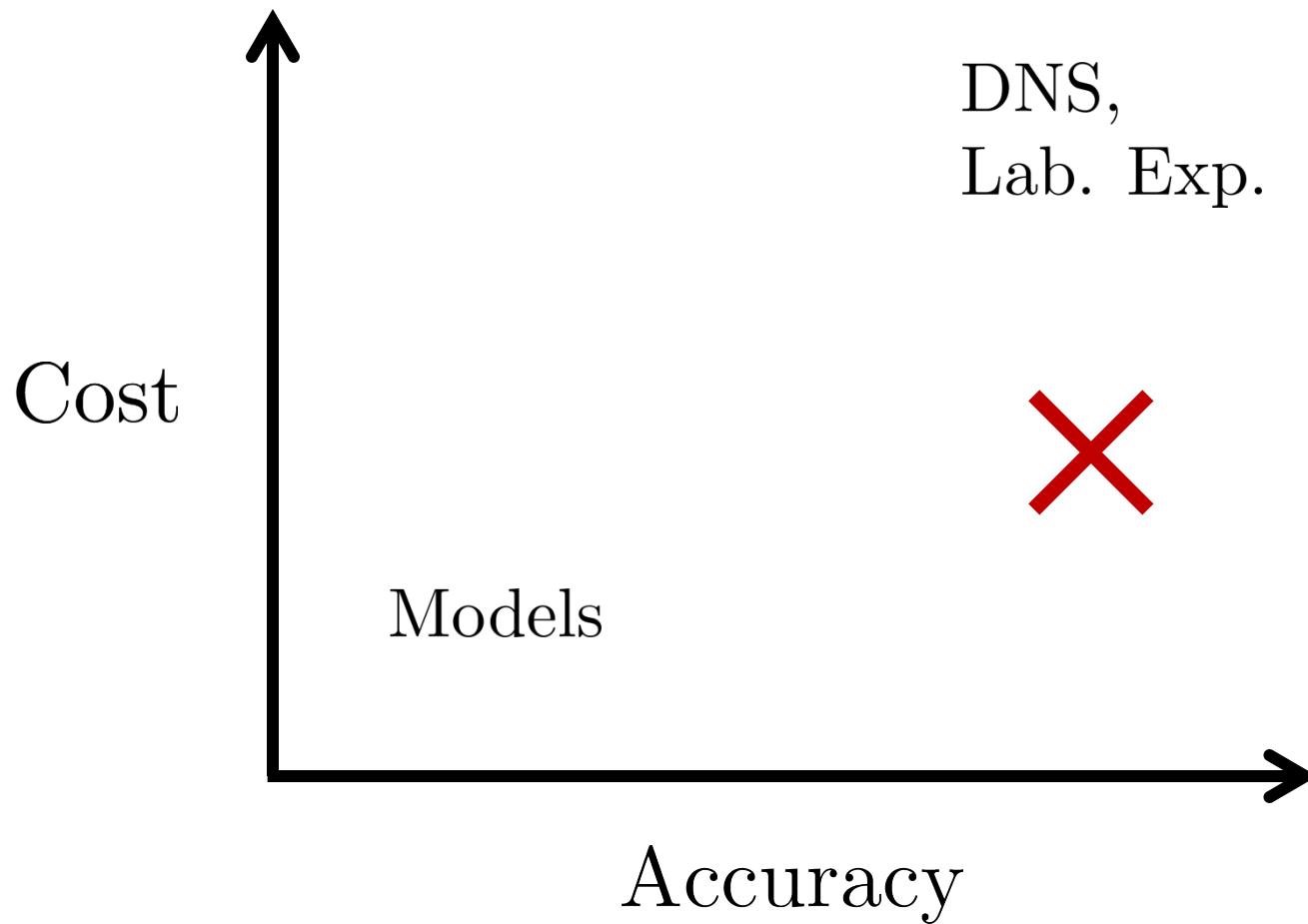
Involve  $k_{mean}$ ,  $k_{max}$ ,  $k_{rms}$ , skewness, silhouette area...

Direct estimates through laboratory experiments

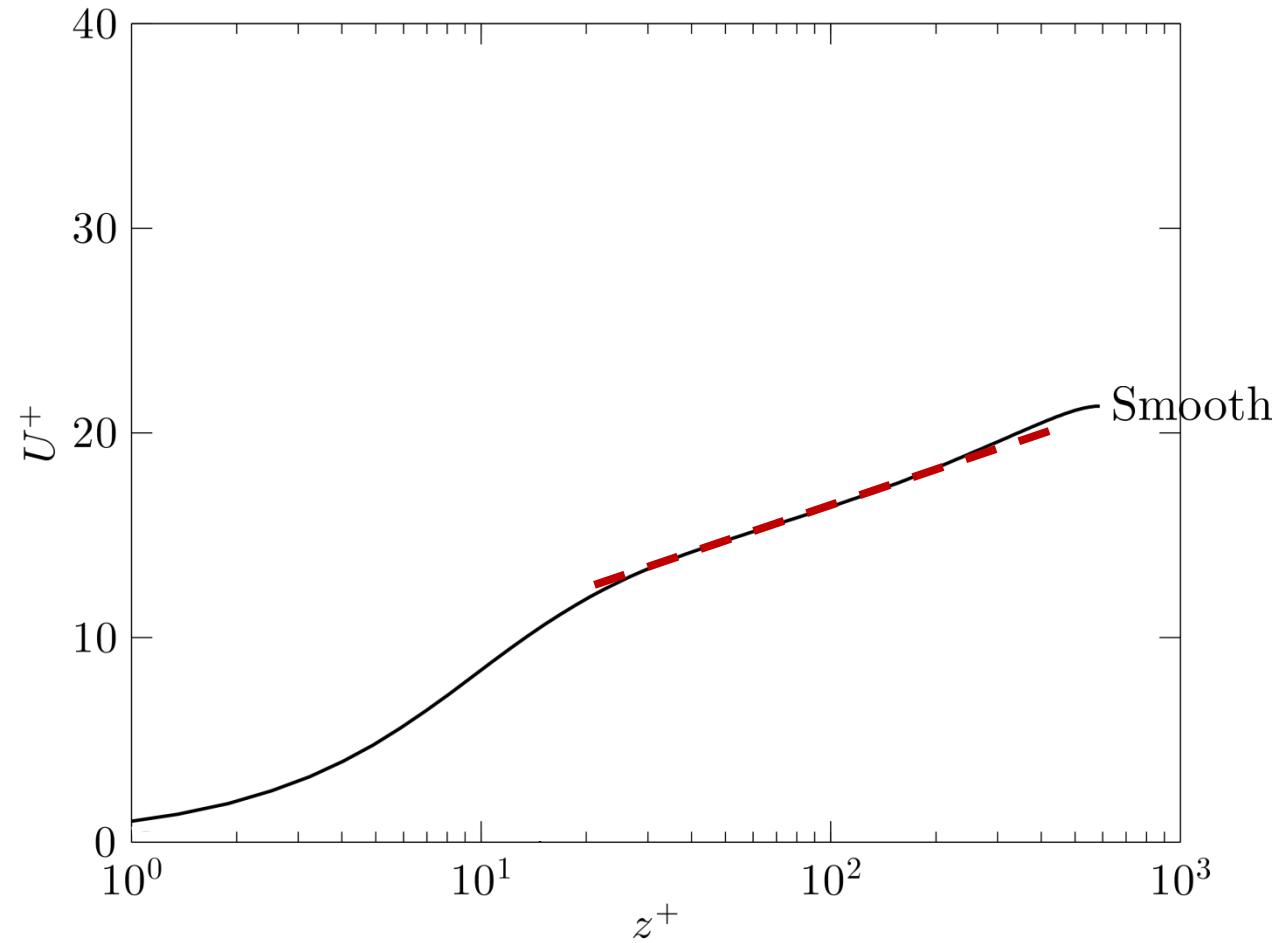


... or conventional  
Direct Numerical Simulations (DNS)

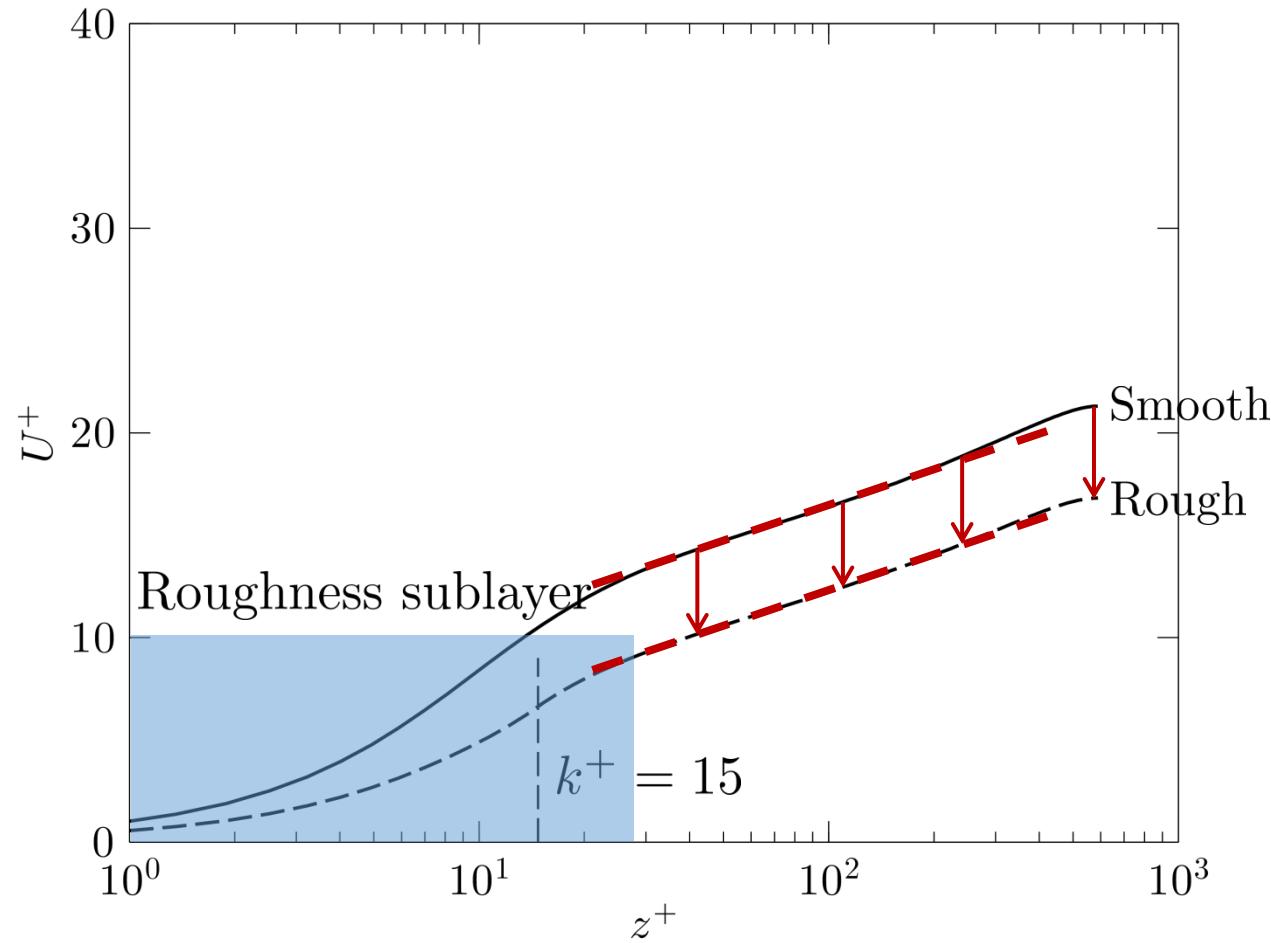
# Objectives



# Background



# Background



# Background

At distances from the wall large compared with the extent of the flow patterns set up by the individual roughness elements, the turbulent flow is unlikely to be affected by the exact nature of the roughness and, as with the smooth wall, it will be determined by the averaged wall shear stresses, the channel height and the fluid viscosity

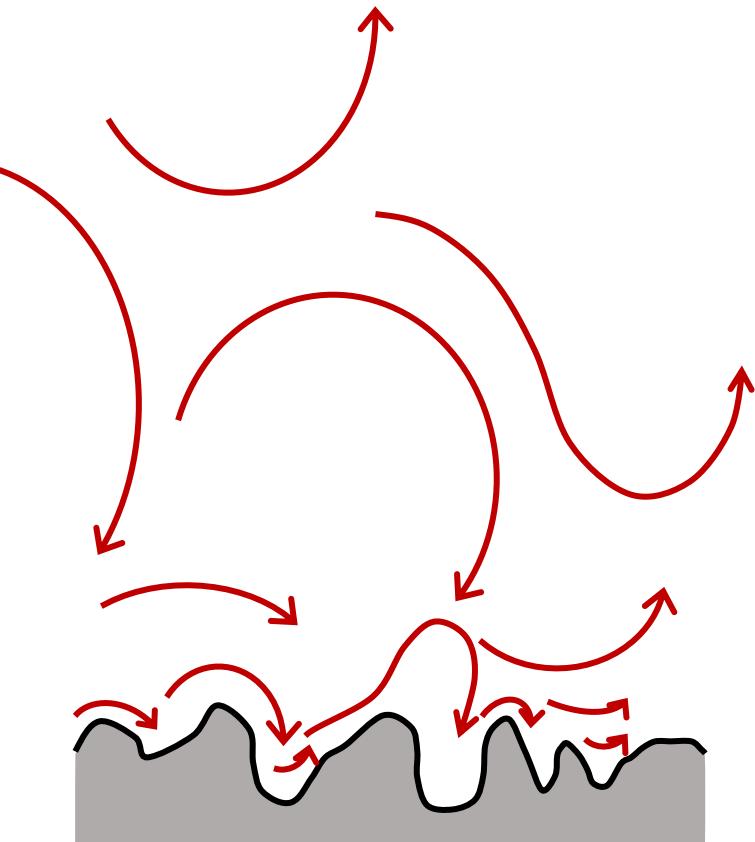
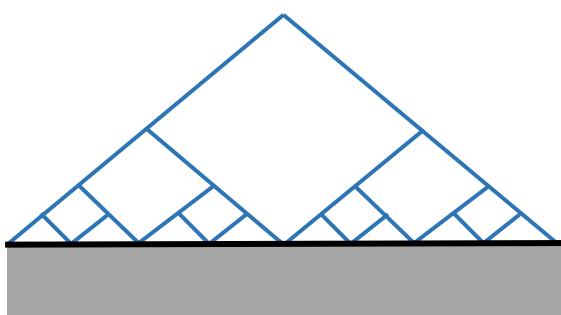
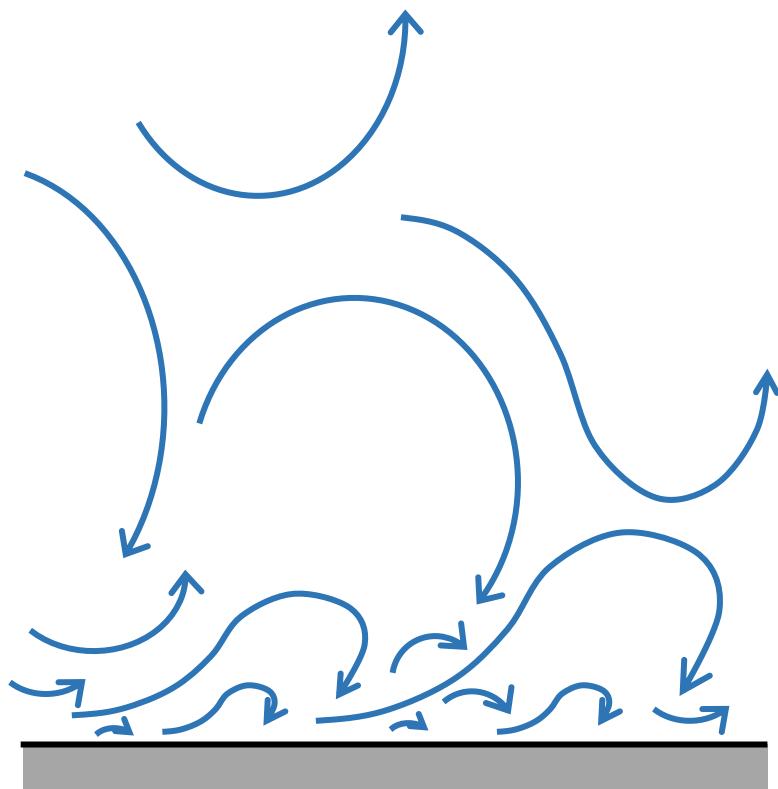
Townsend (1956)

For  $z \gg k$ ,  $(U_\infty - U)/U_\tau = f(z/h)$

$$\frac{h}{k} > 20\text{--}40$$

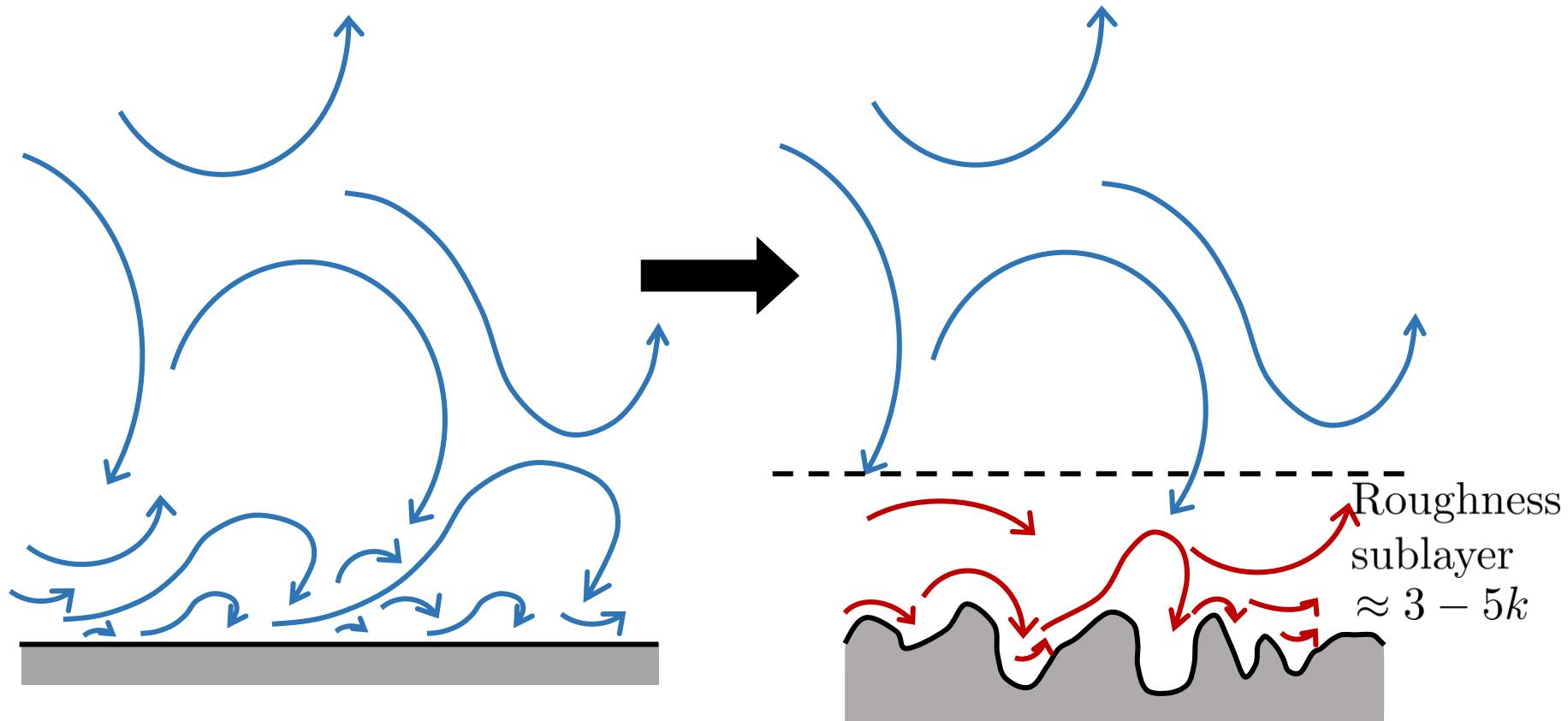
Raupach (1982), Flack *et al.* (2005), Flores & Jiménez (2006), Shockling *et al.* (2006), Coceal *et al.* (2006), Leonardi & Castro (2010), Hultmark *et al.* (2013), Chan *et al.* (2015), Squire *et al.* (2016) ...

# Background



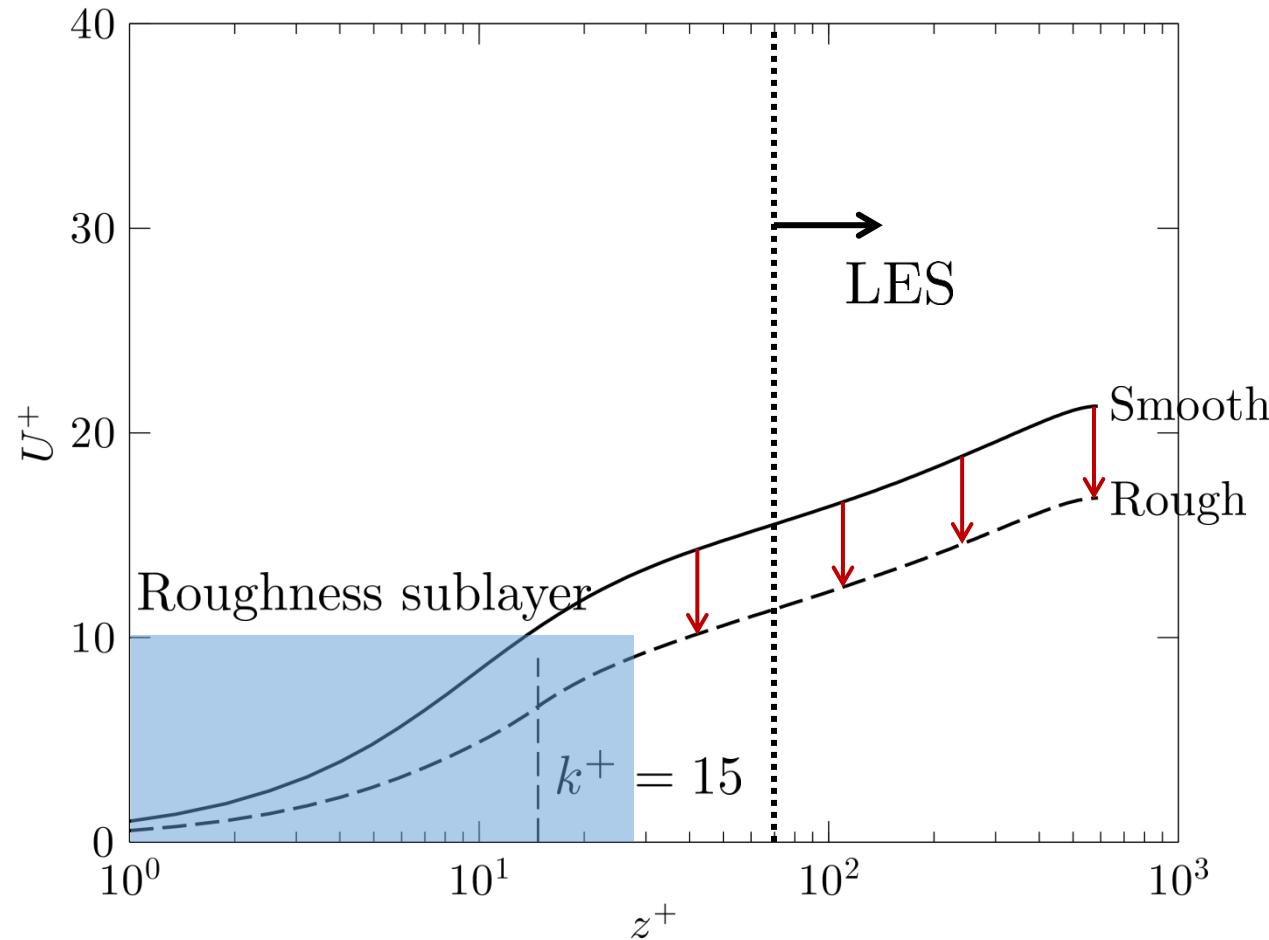
Townsend (1956)

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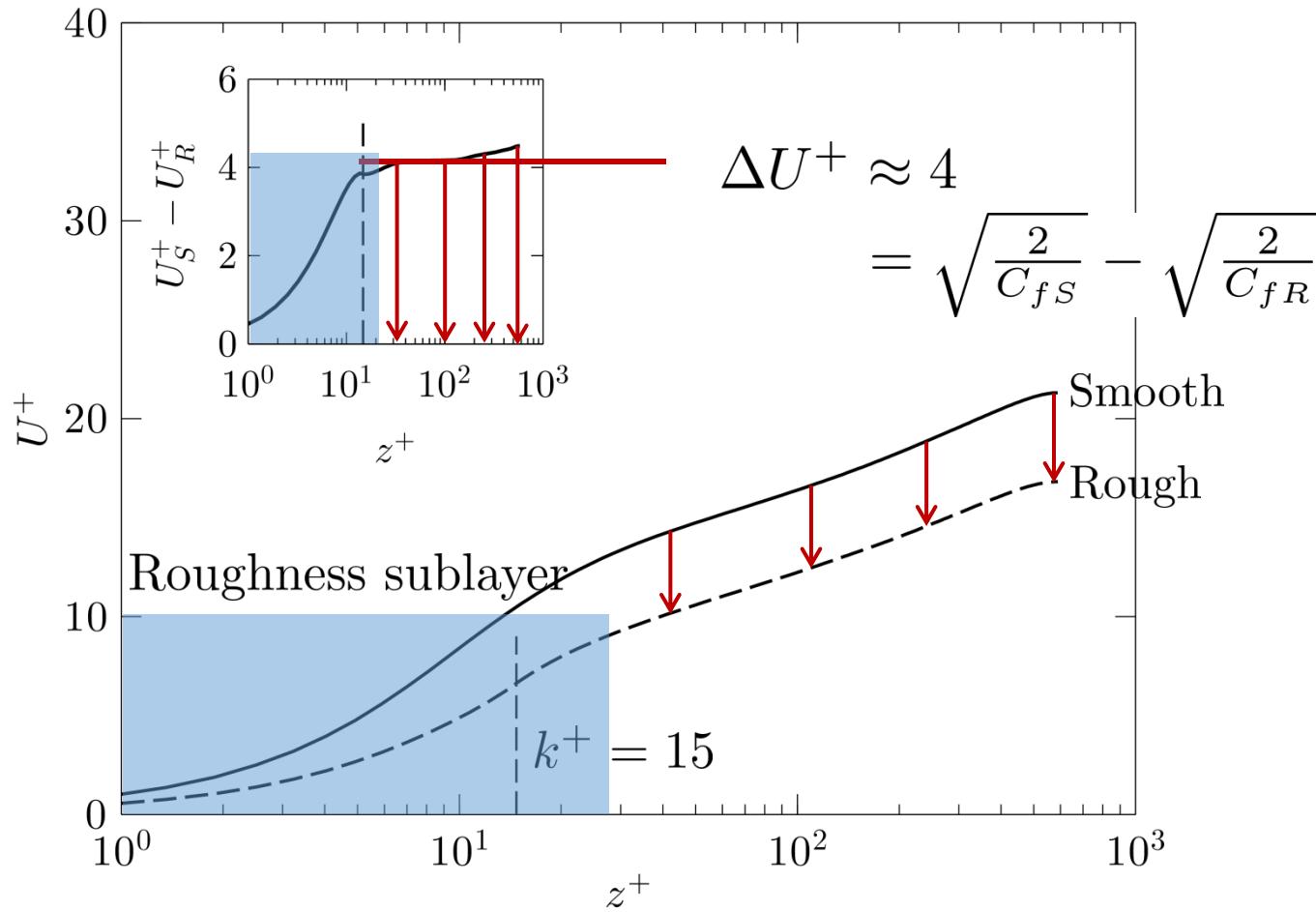


Townsend (1956)

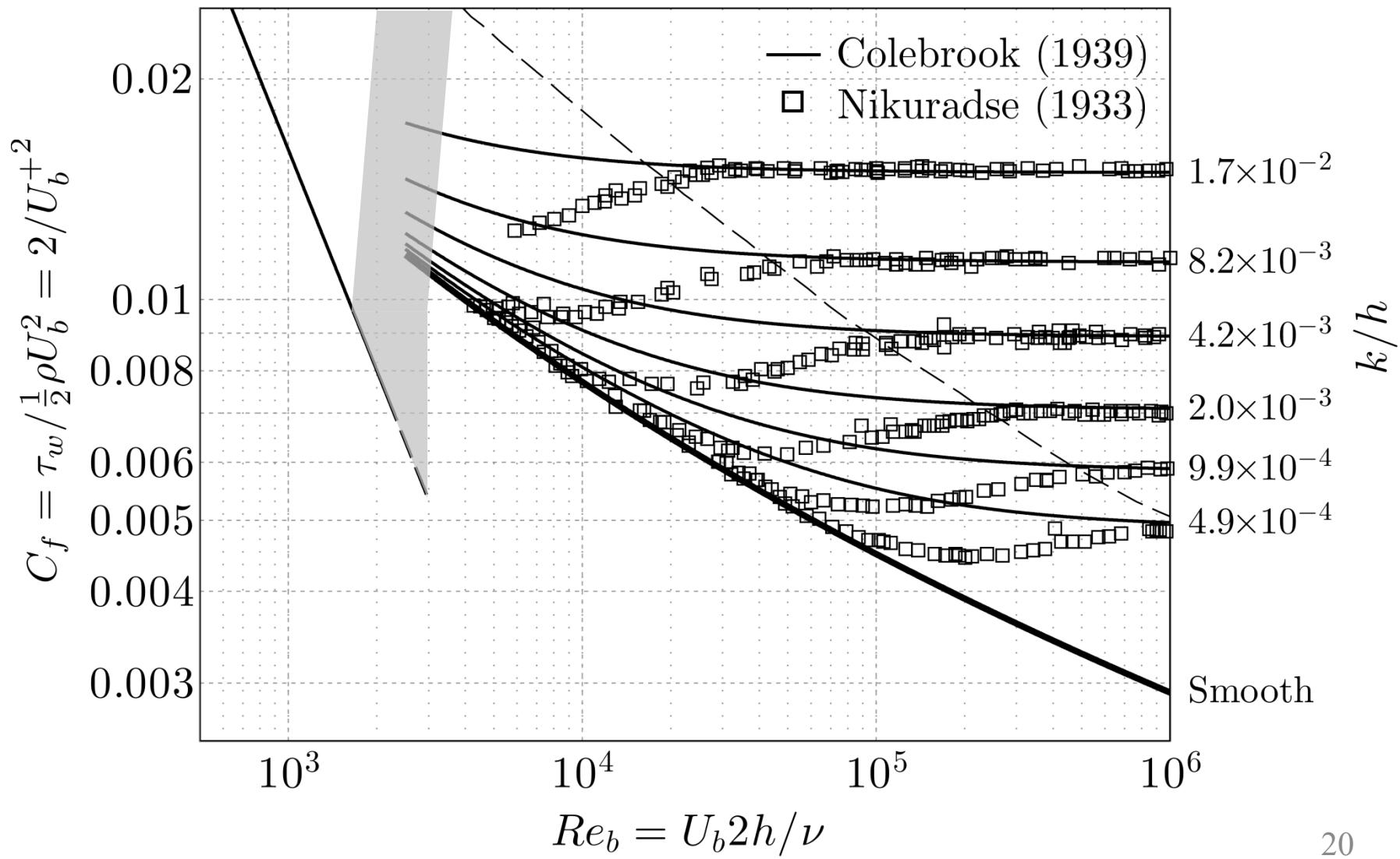
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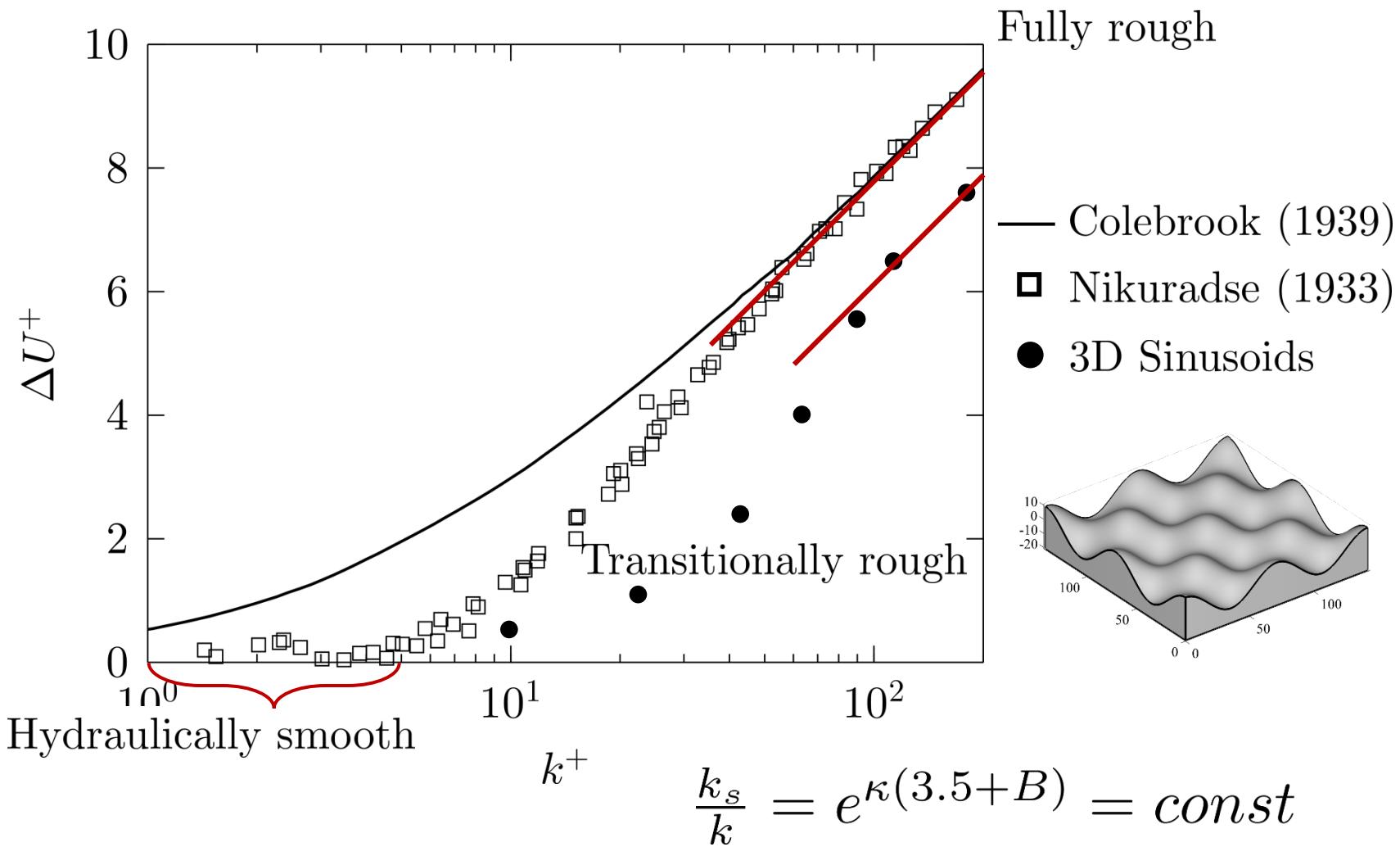
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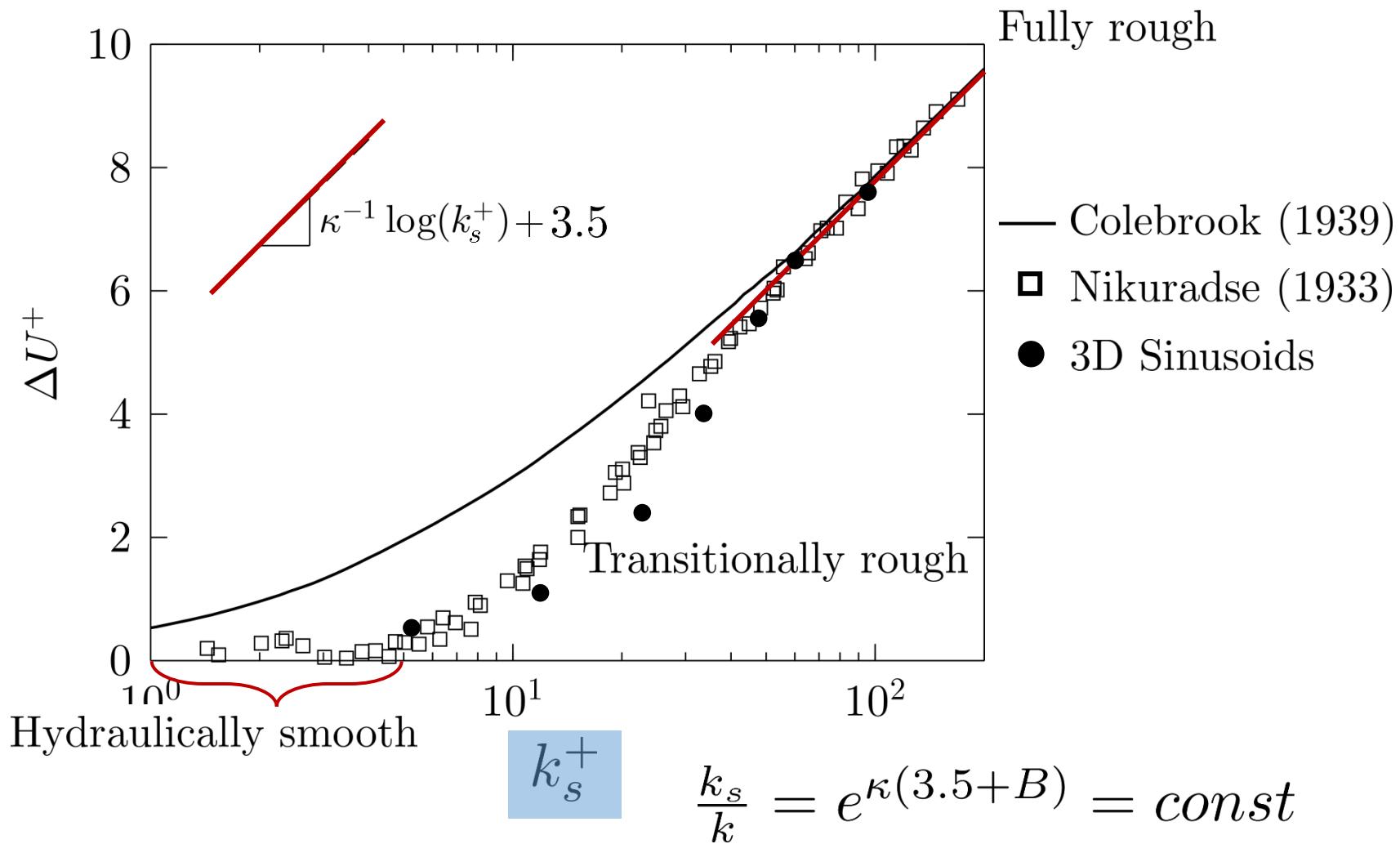
# Motivation



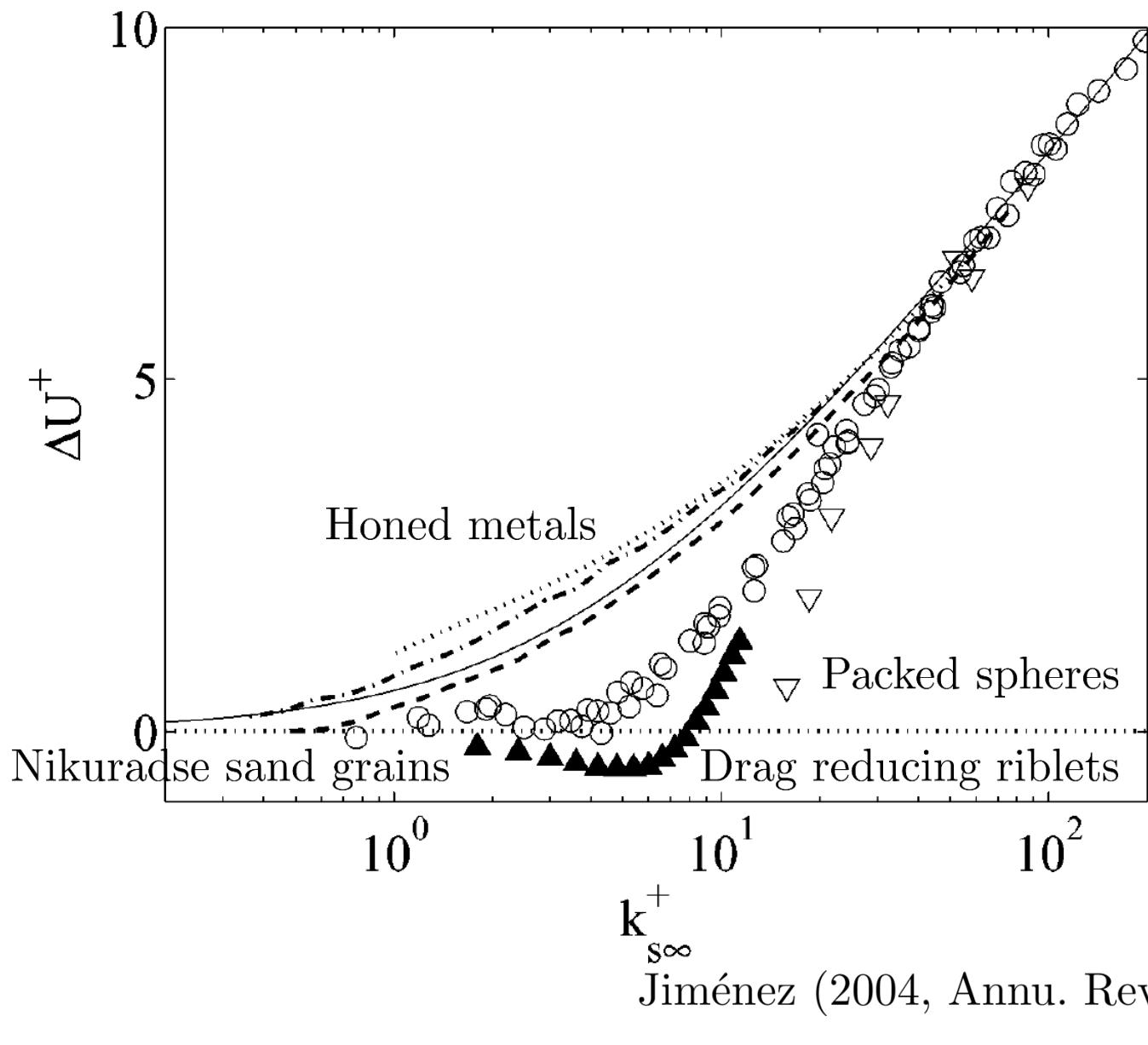
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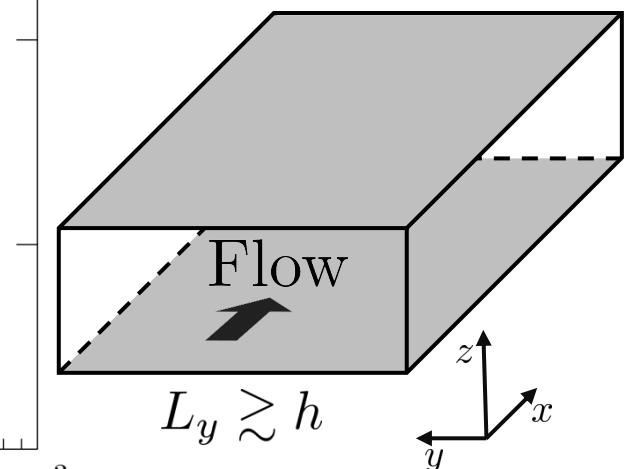
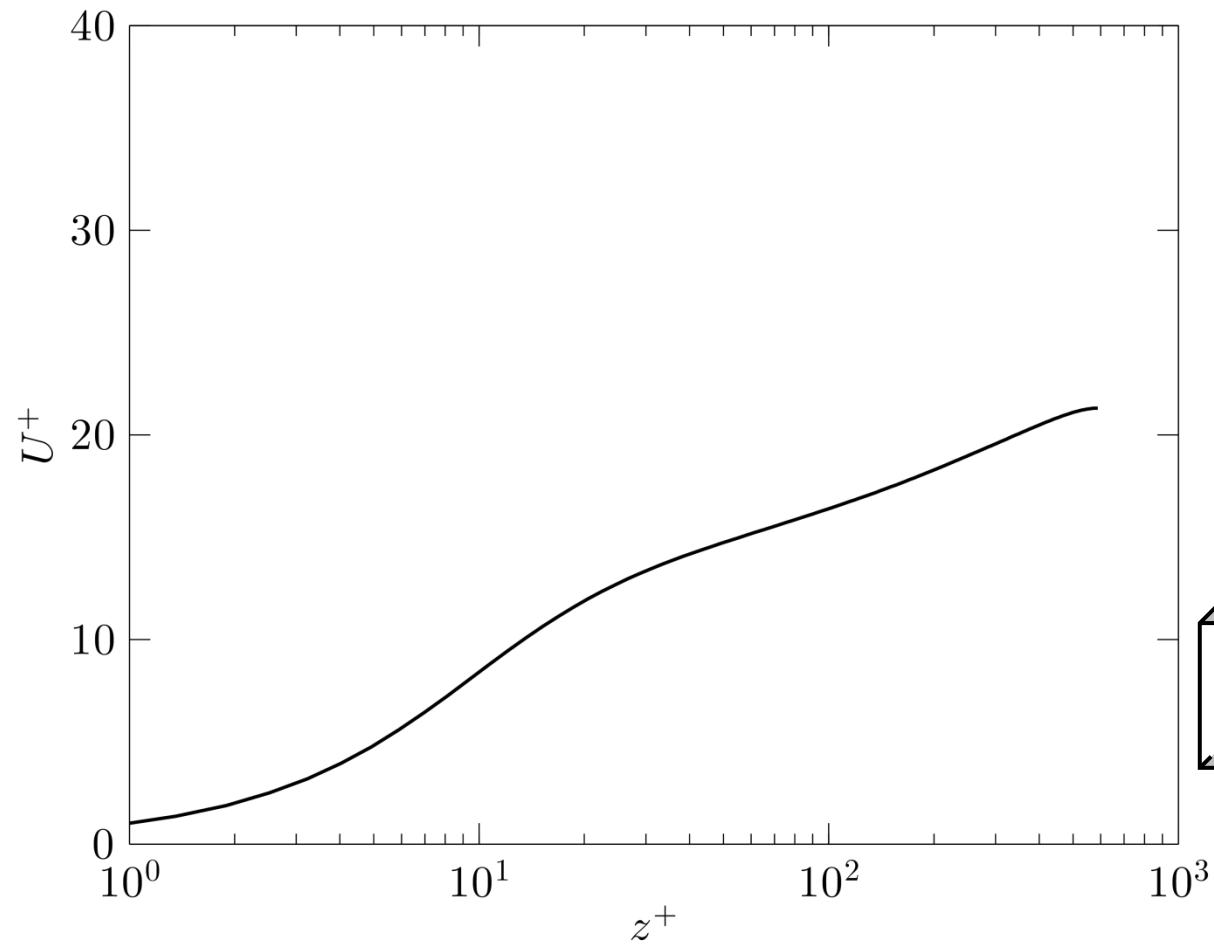
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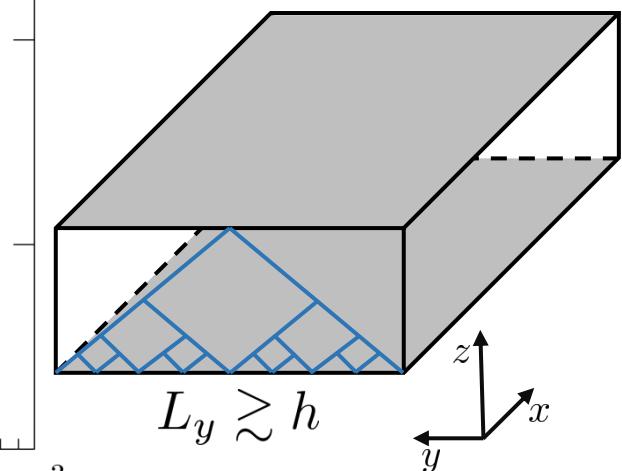
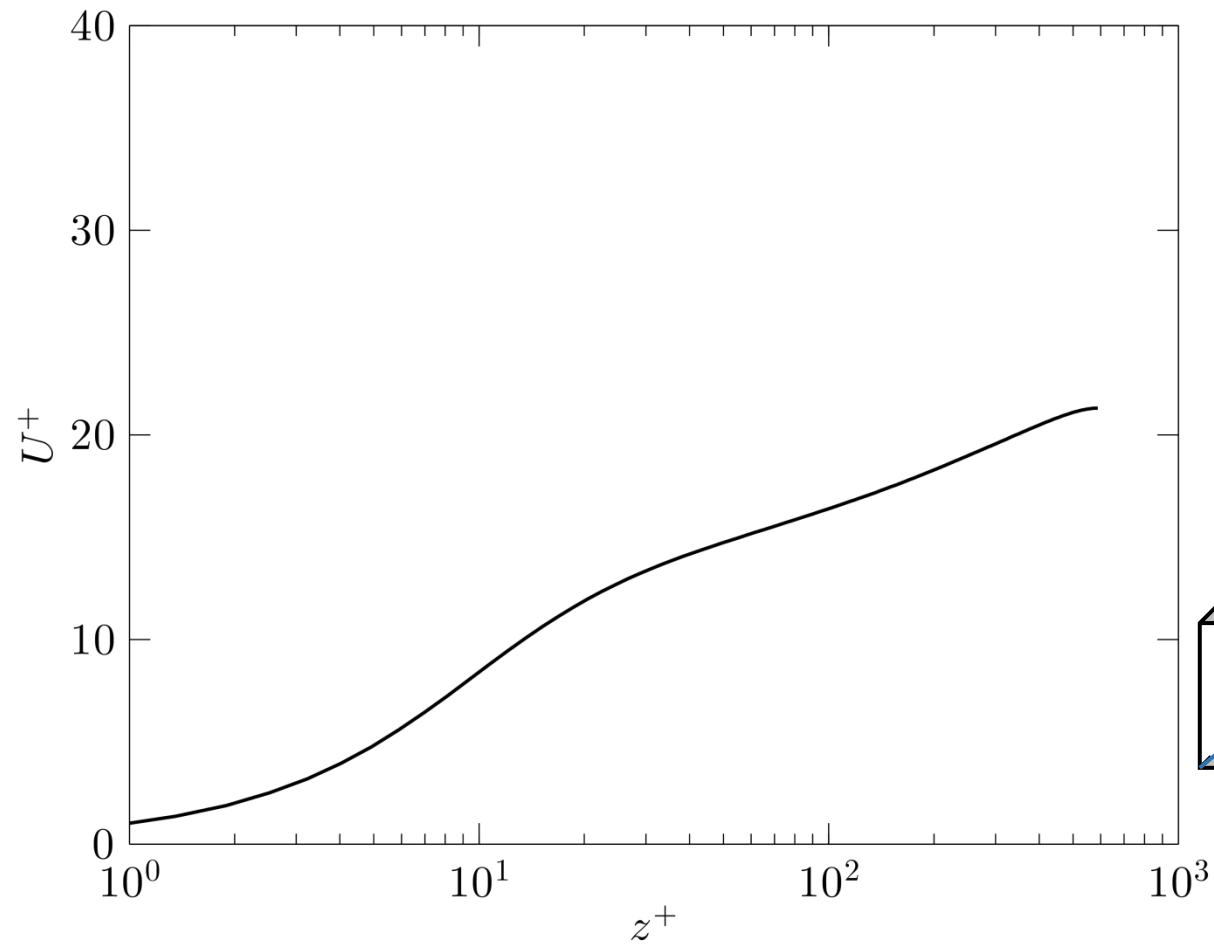
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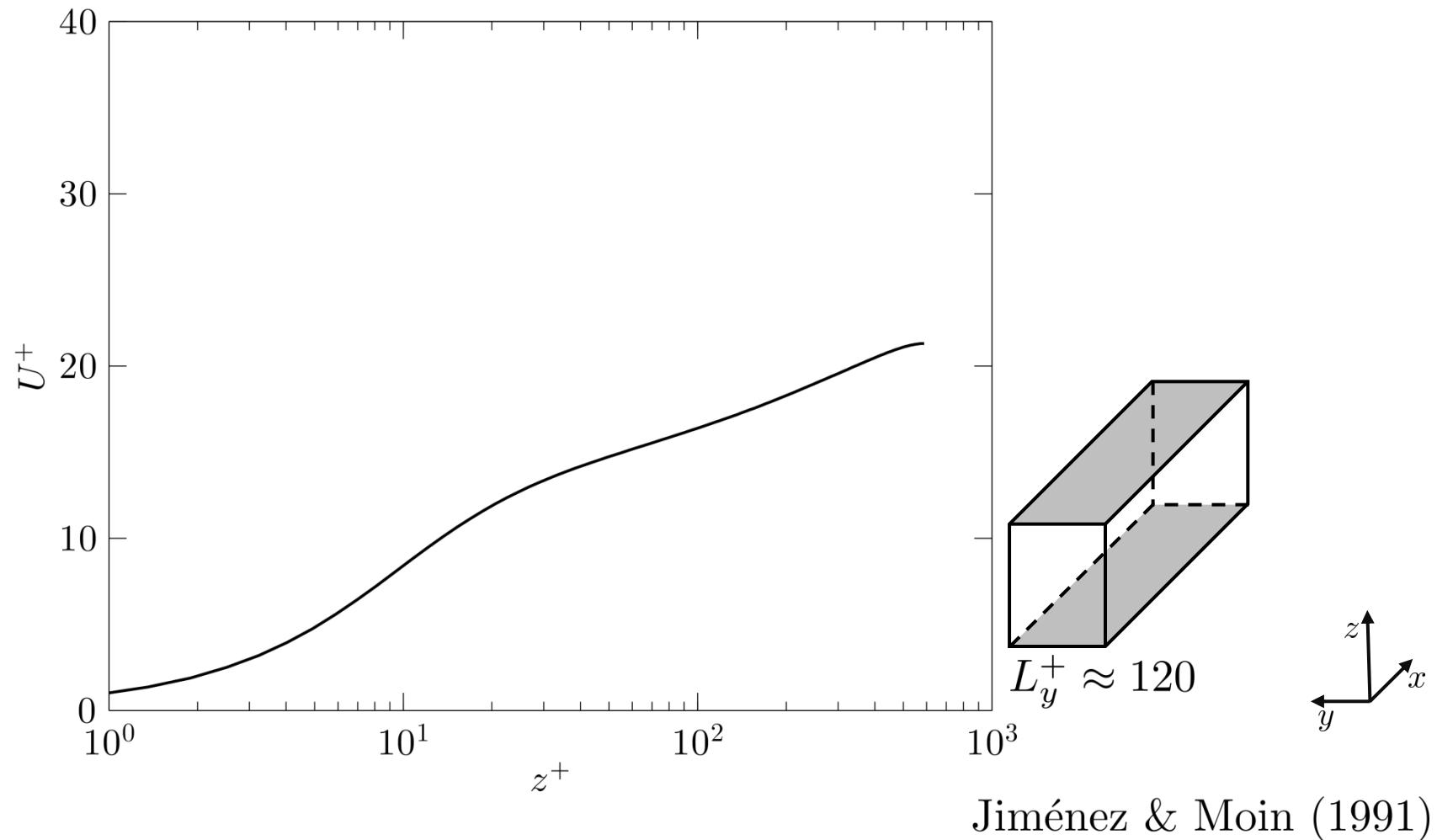
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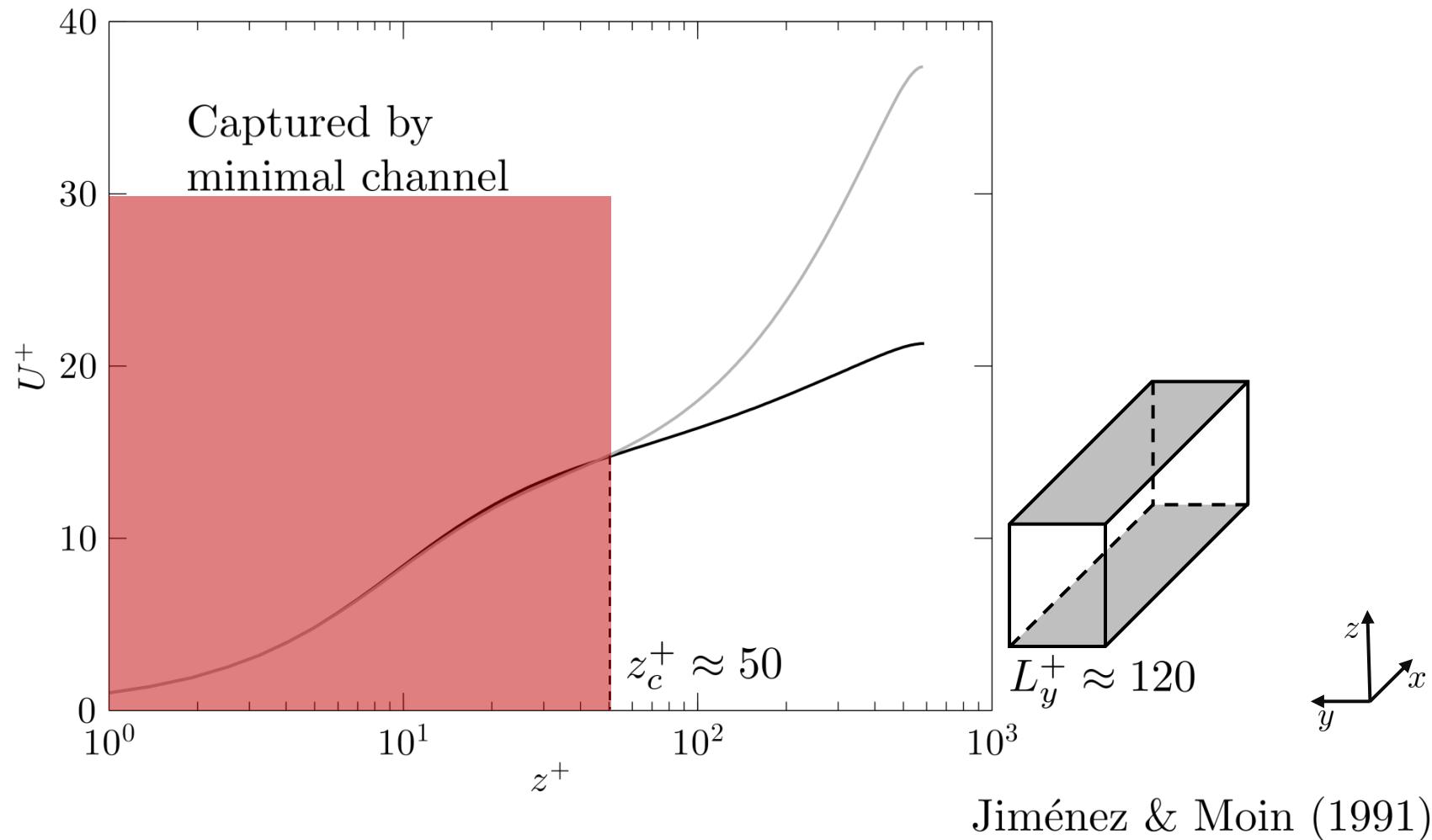
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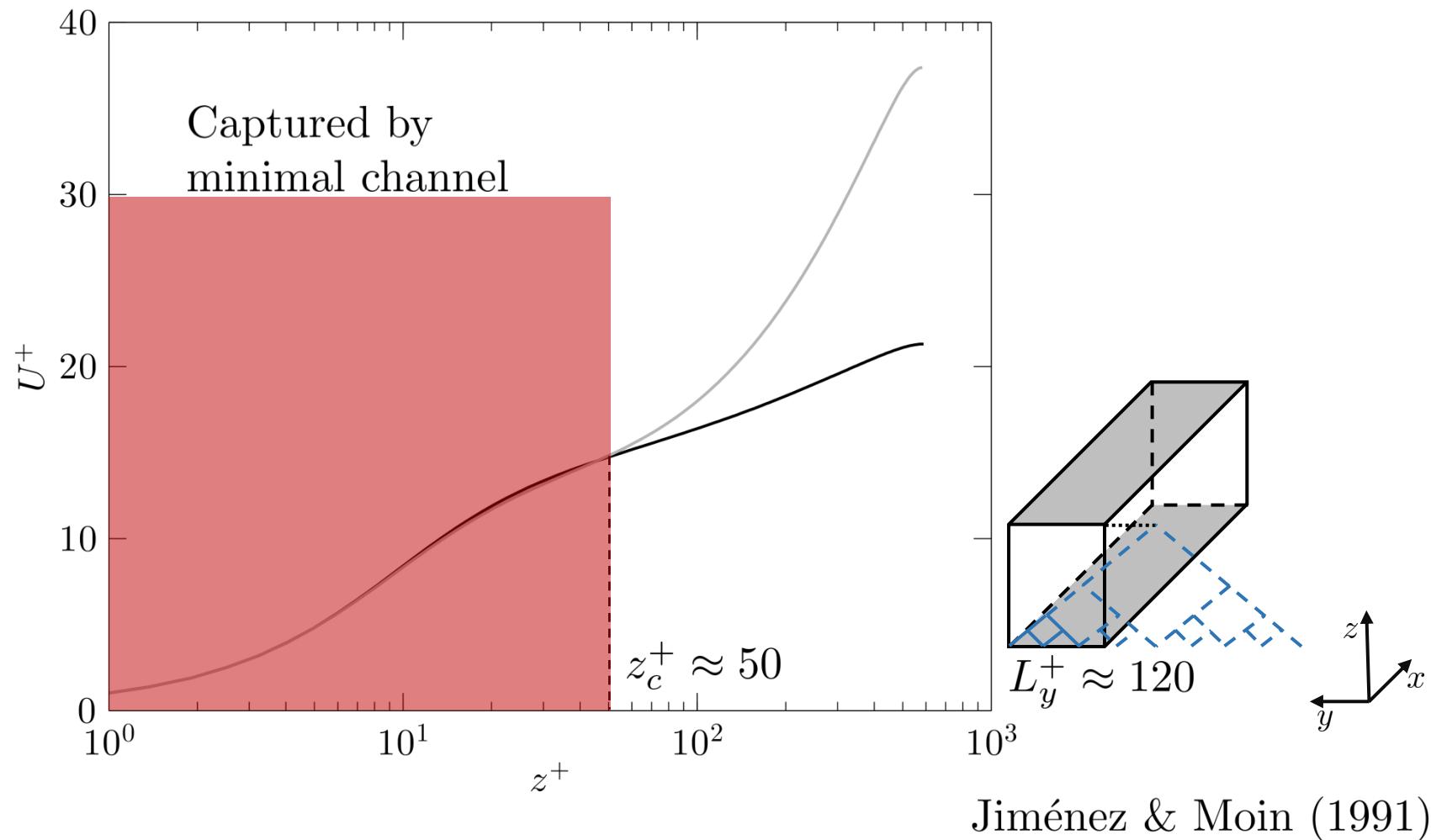
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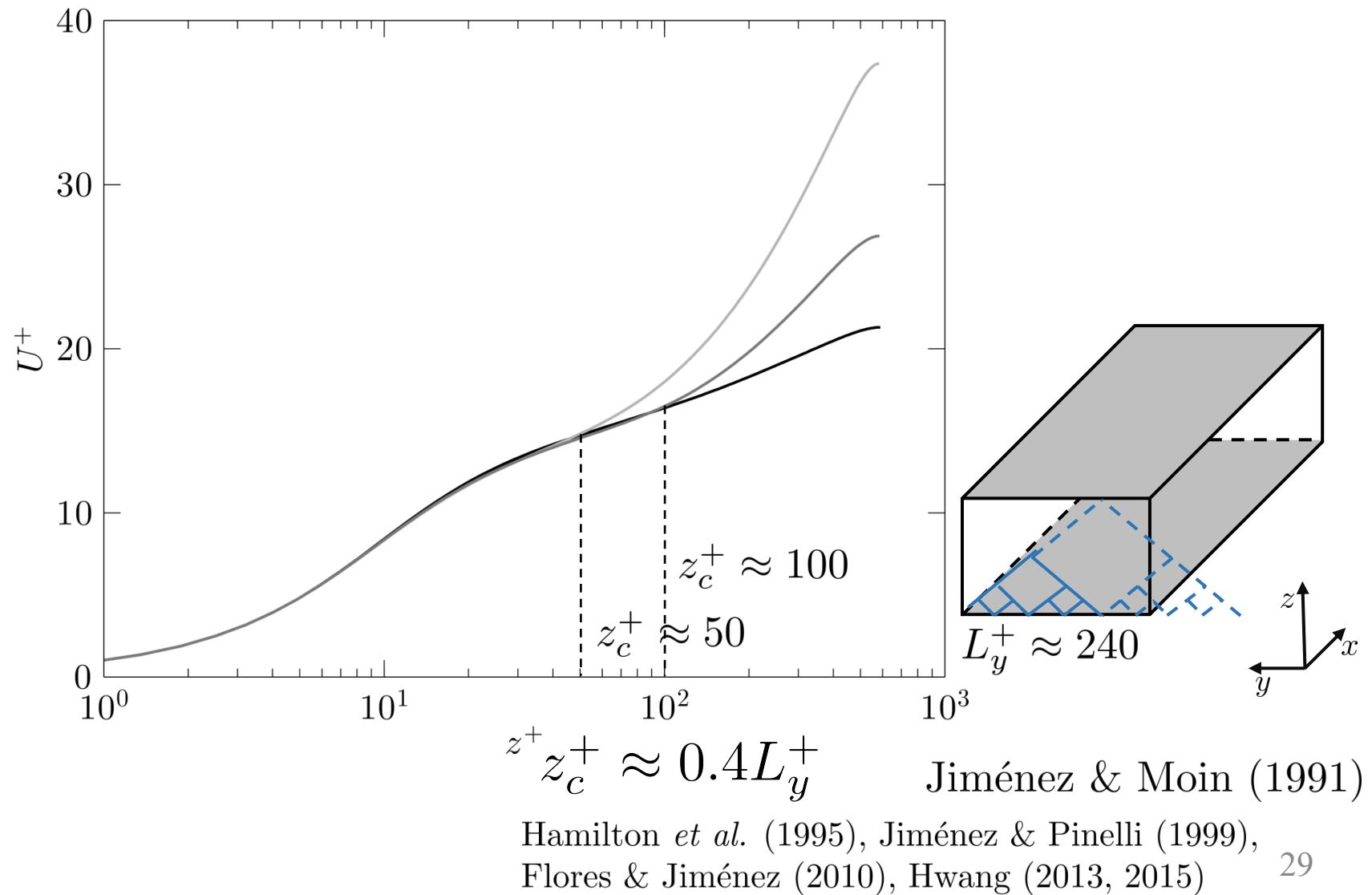
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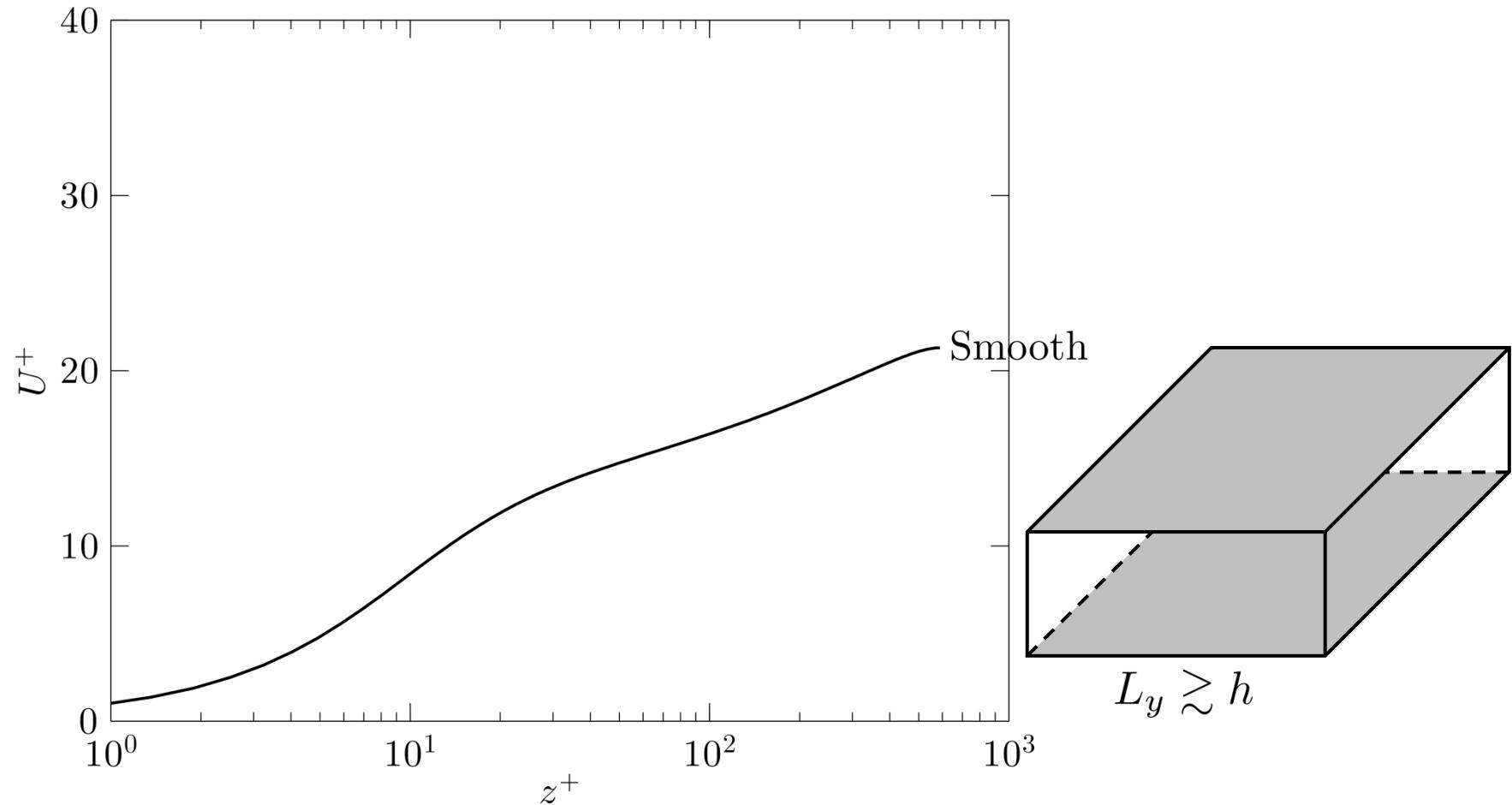


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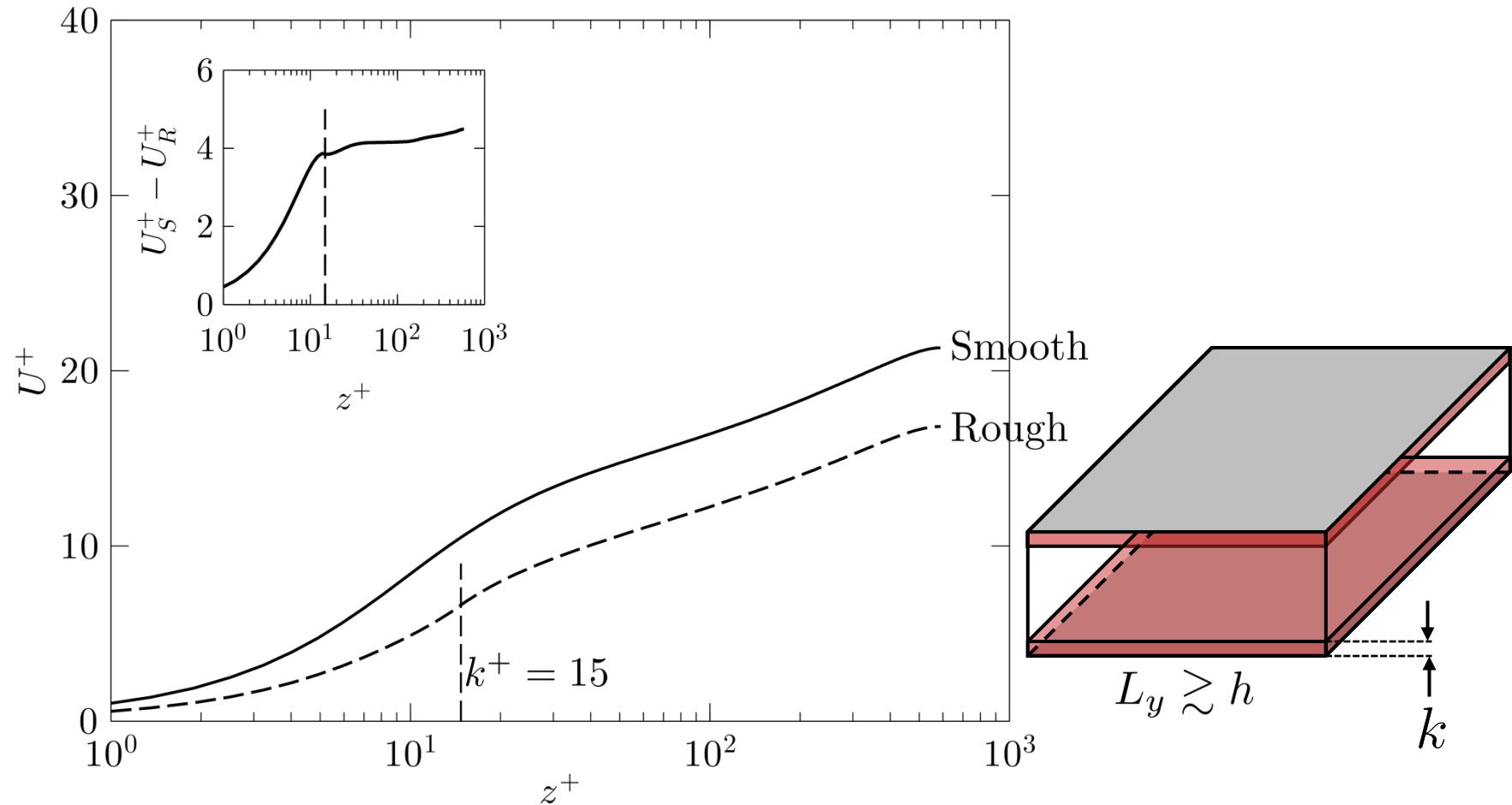
# Minimal-Span Channel

Chung, Chan, MacDonald, Hutchins, Ooi (2015)



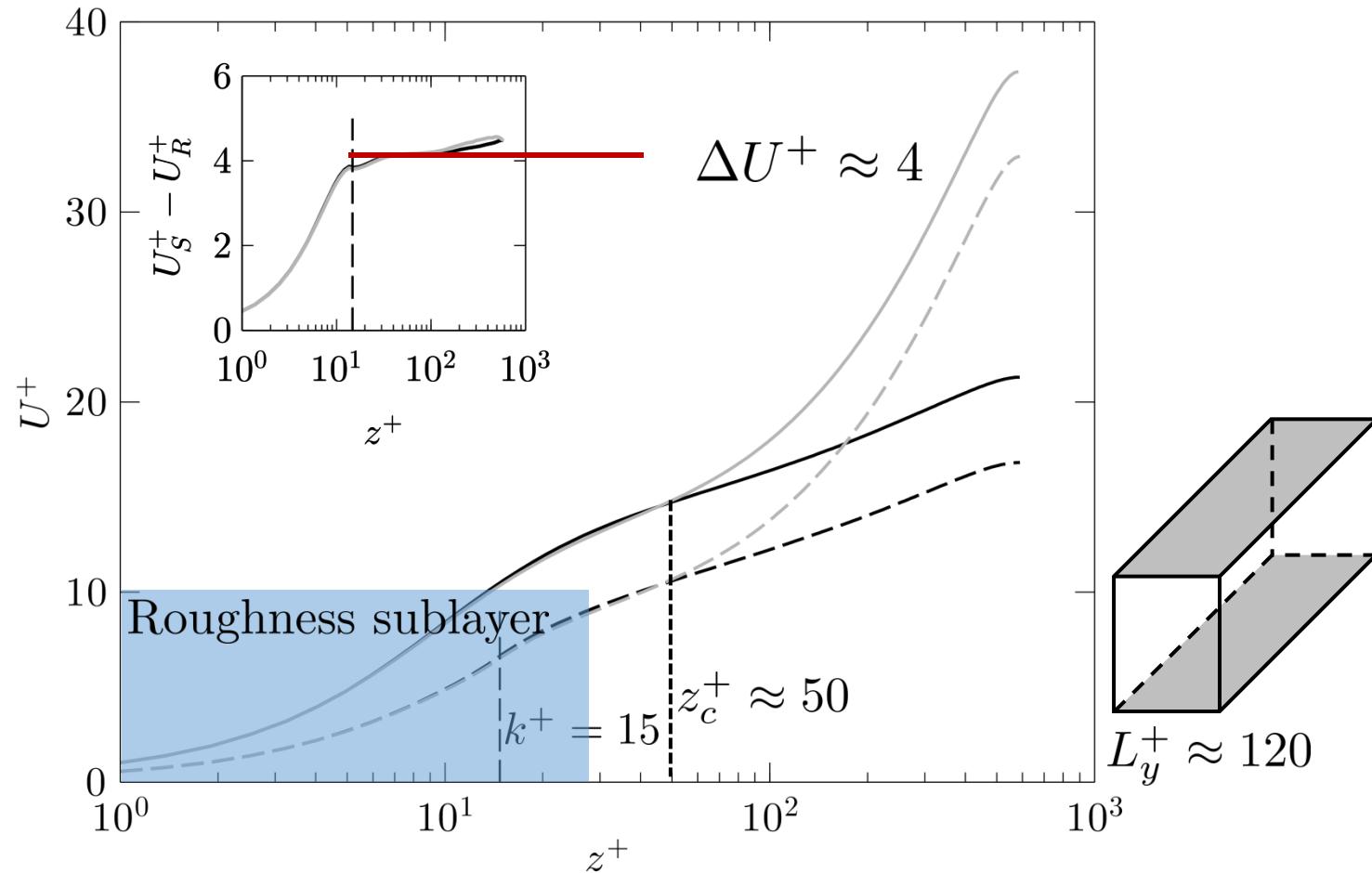
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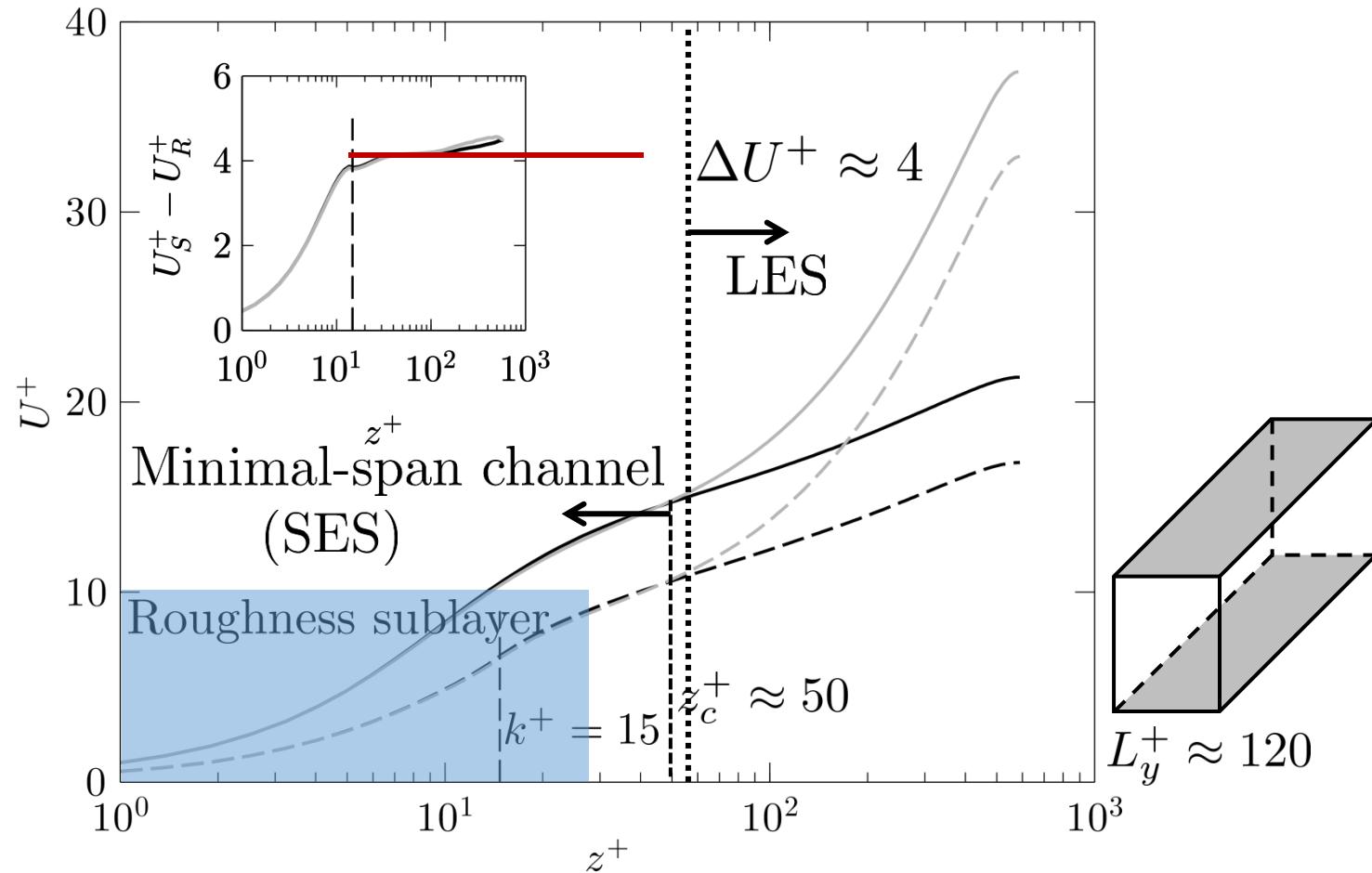
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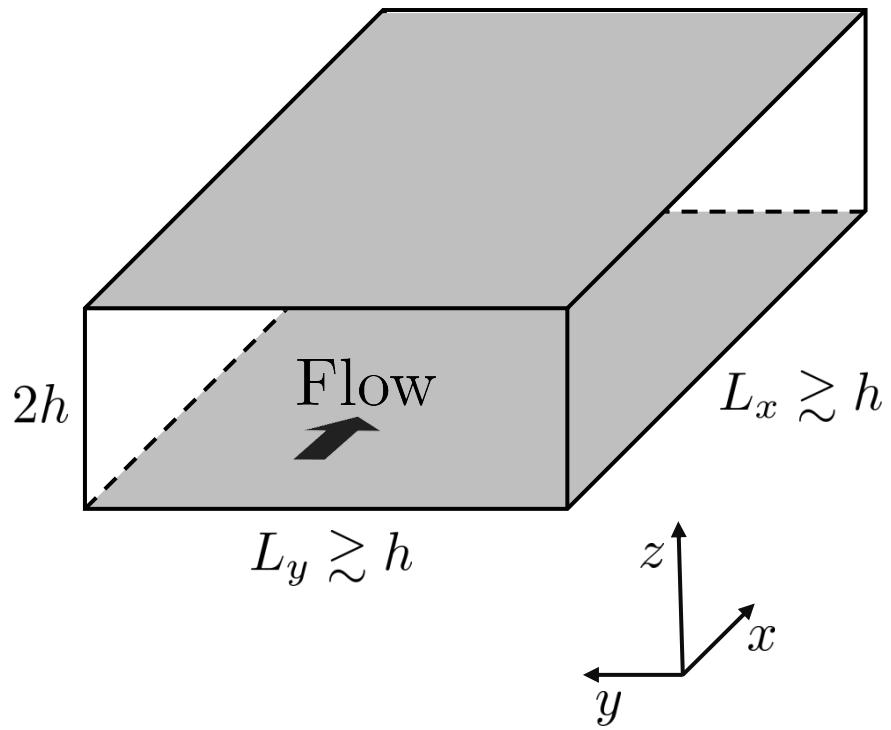
# Minimal-Span Channel

$$Re_\tau = 590$$

$$N_{cells} \approx 55 \text{ million}$$

$$\text{CPU hours} \approx 20,000$$

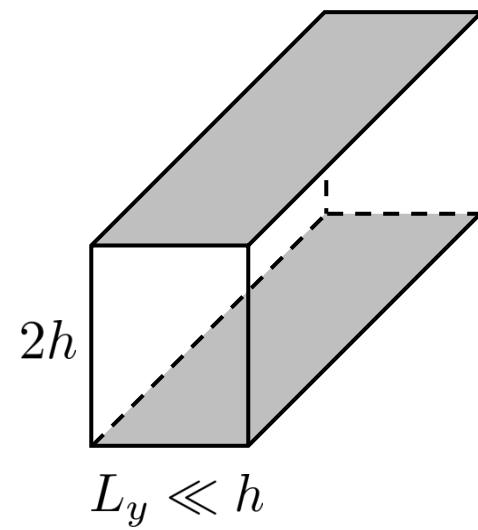
$$\$800$$



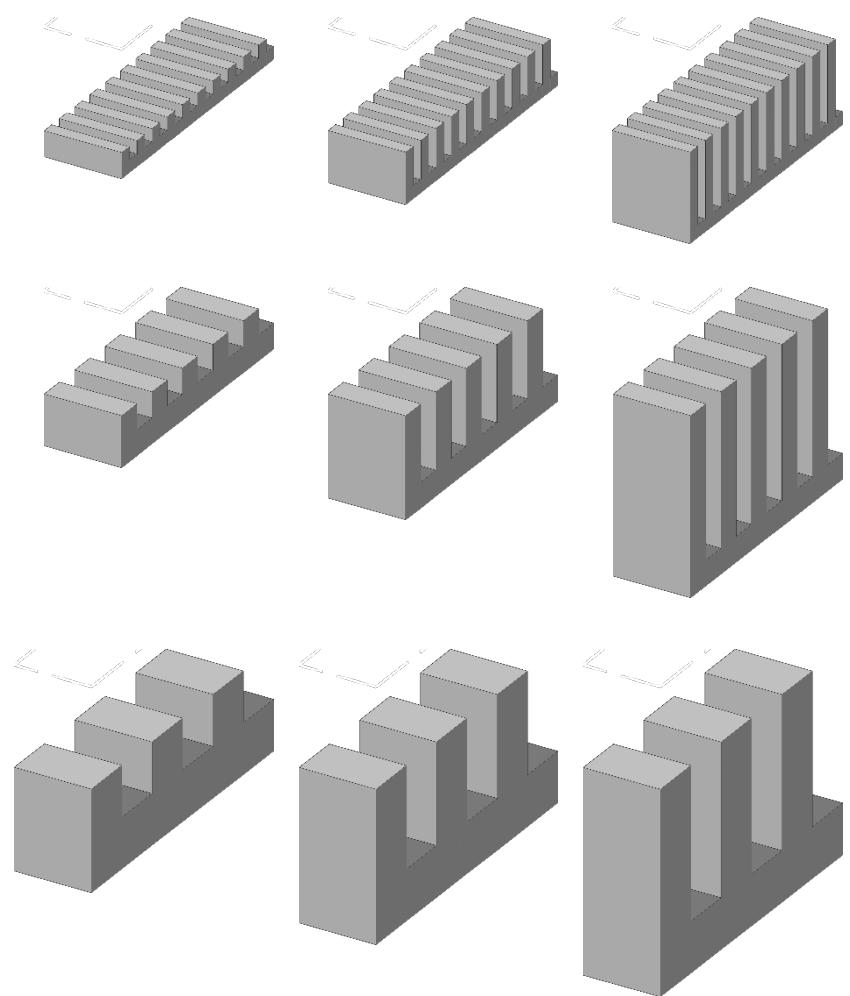
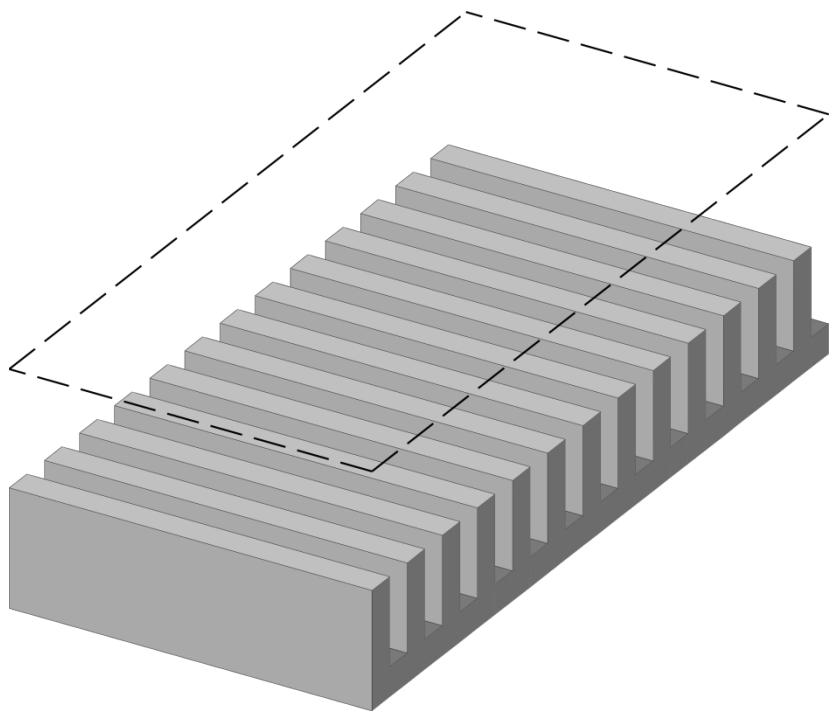
$$N_{cells} \approx 1 \text{ million}$$

$$\text{CPU hours} \approx 1,300$$

$$\$52$$



# Minimal-Span Channel



# Minimal-Span Channel

Chung, Chan, MacDonald, Hutchins, Ooi (2015)

$$L_y^+ \geq \max(100, \quad k^+/0.4, \quad \lambda_{r,y})$$

$$z_c^+ > k^+$$

$$z_c^+ \approx 0.4L_y^+$$

# Minimal-Span Channel

Chung, Chan, MacDonald, Hutchins, Ooi (2015)

$$L_y^+ \geq \max(100, k^+/0.4, \lambda_{r,y})$$

MacDonald, Chung, Hutchins, Chan, Ooi, García-Mayoral (2017)

$$L_x^+ \geq \max(3L_y^+, 1000, \lambda_{r,x})$$

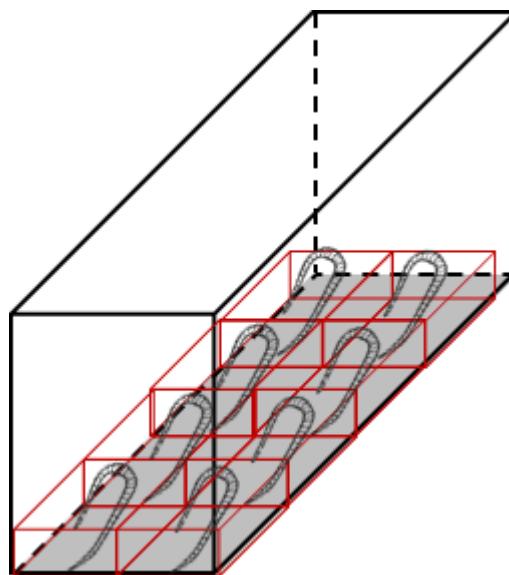
Run time

95% confidence interval,  $\Delta U^+ \pm 2.77\epsilon^+ = \Delta U^+ \pm \zeta$

$$\epsilon^+ = K(C^*)^{-1/2}$$

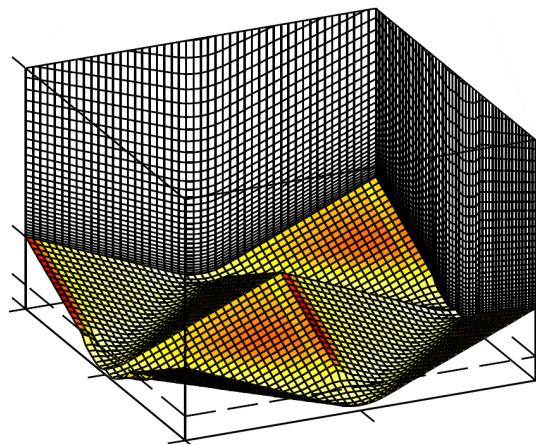
$C^*$  = eddy count

↑  
User-set target



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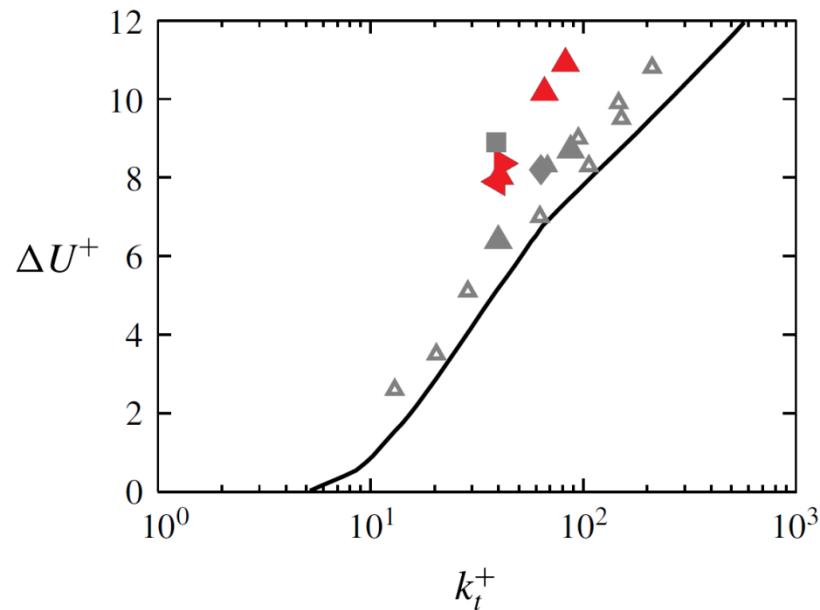
- Use this method to investigate various rough-wall geometries
  - Square-based pyramids



MacDonald *et al.* (2017, JFM)

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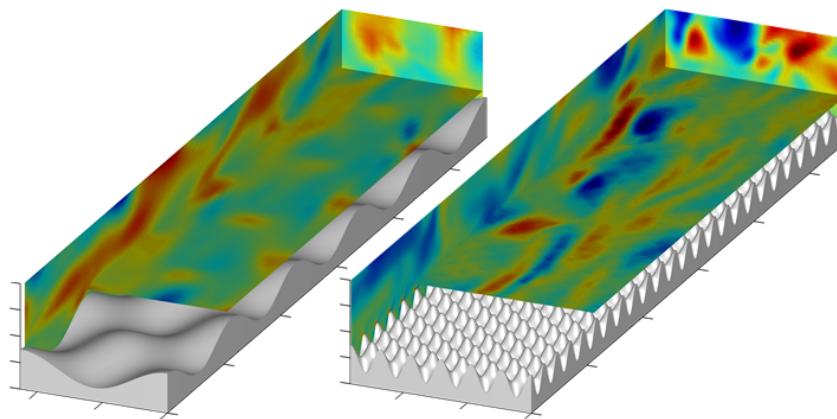
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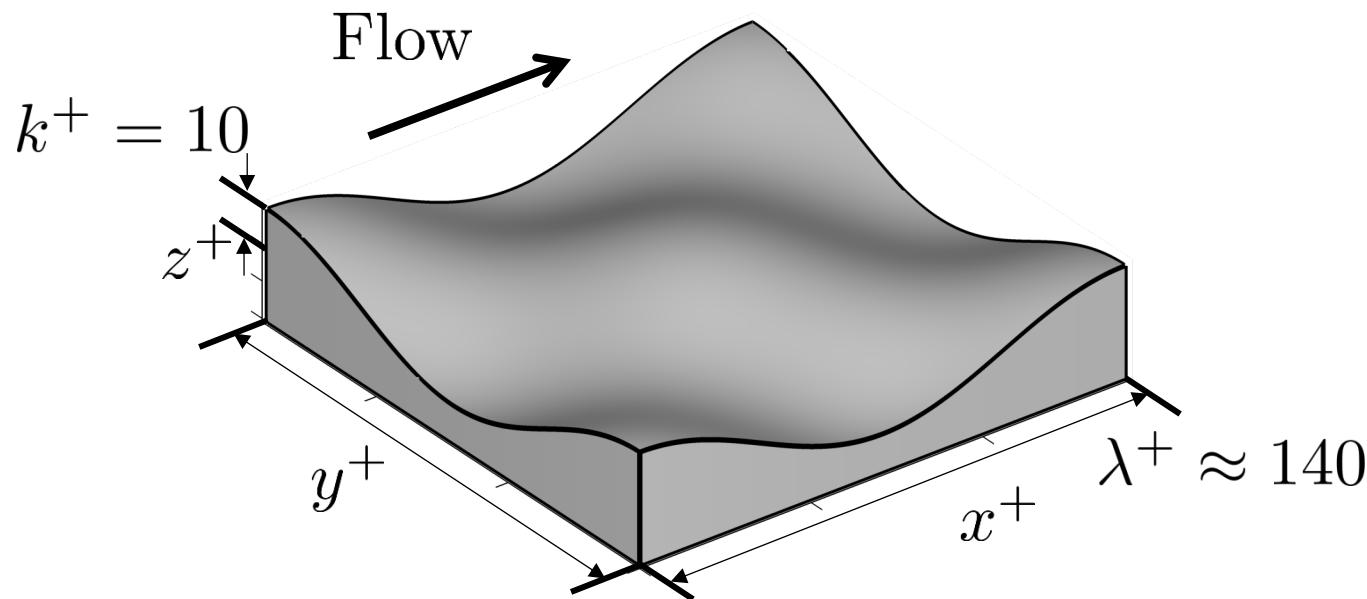
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  - Three-dimensional sinusoidal roughness



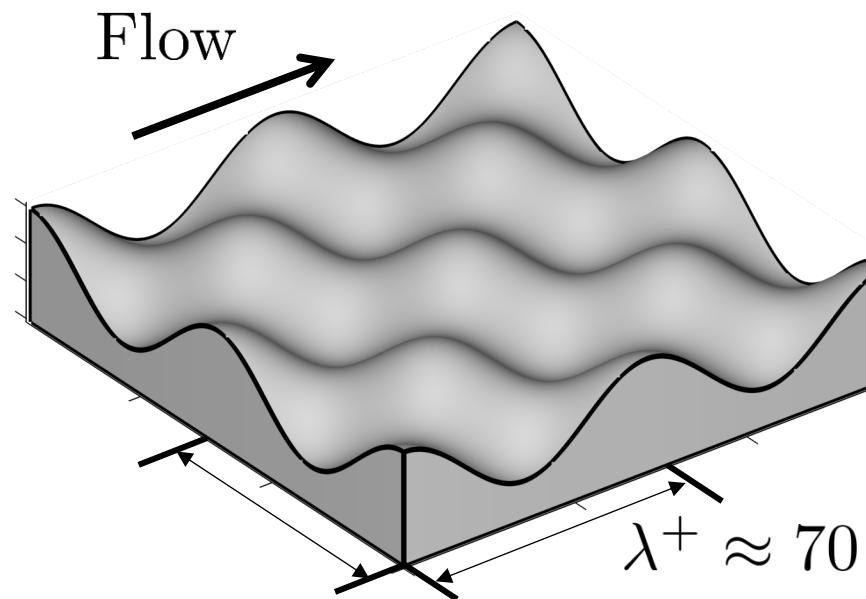
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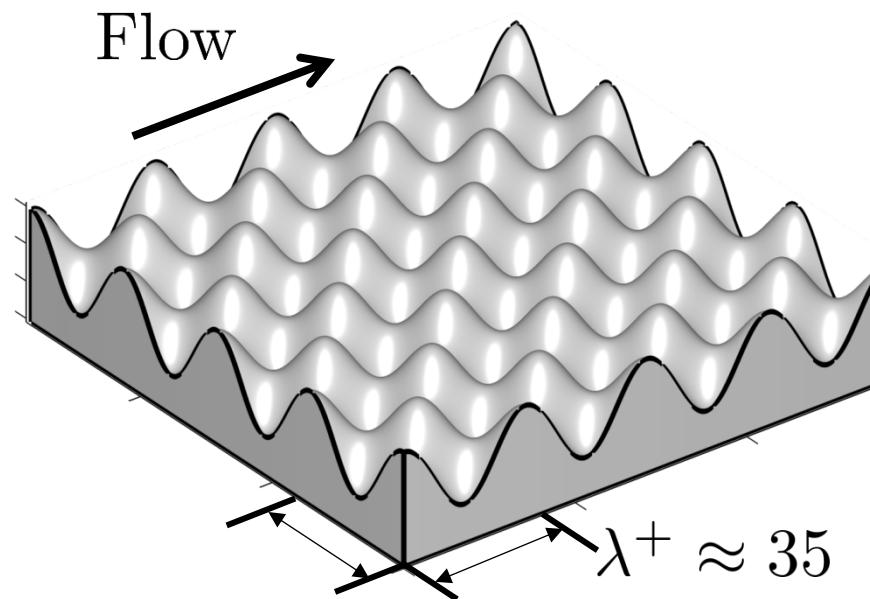
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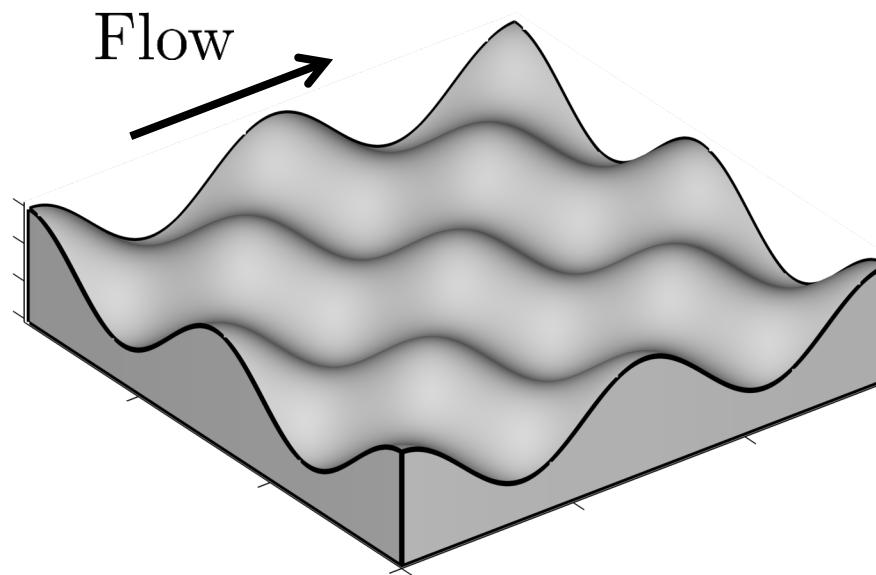
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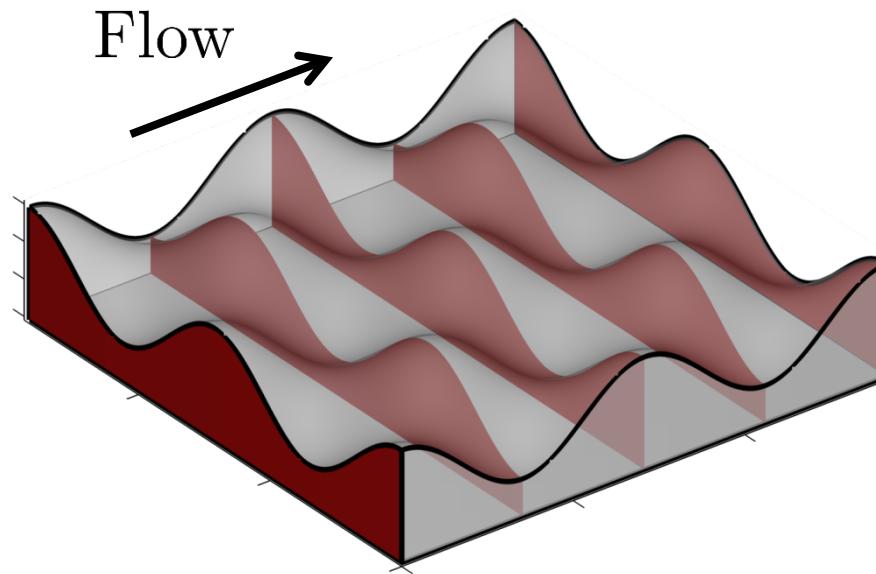
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$$\Lambda = \frac{A_f}{A_p} \text{ (Schlichting 1936)}$$

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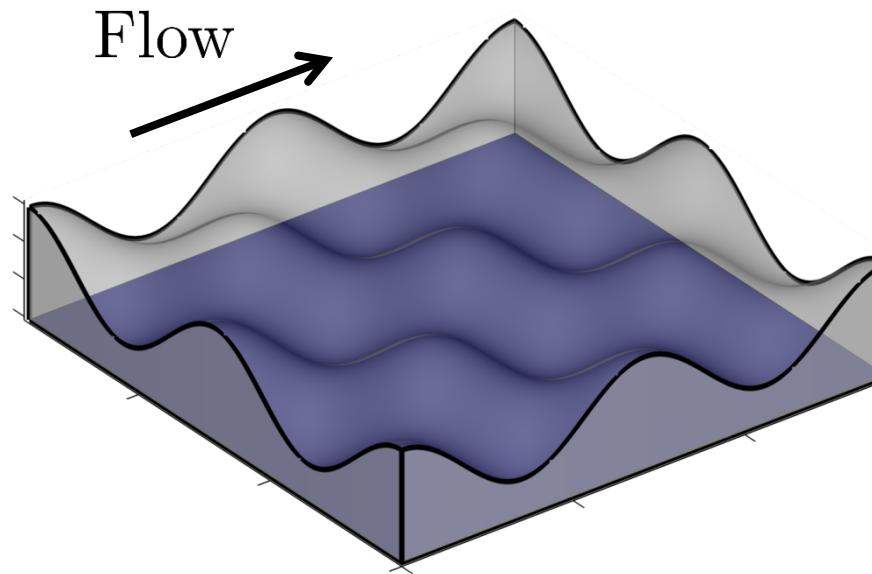
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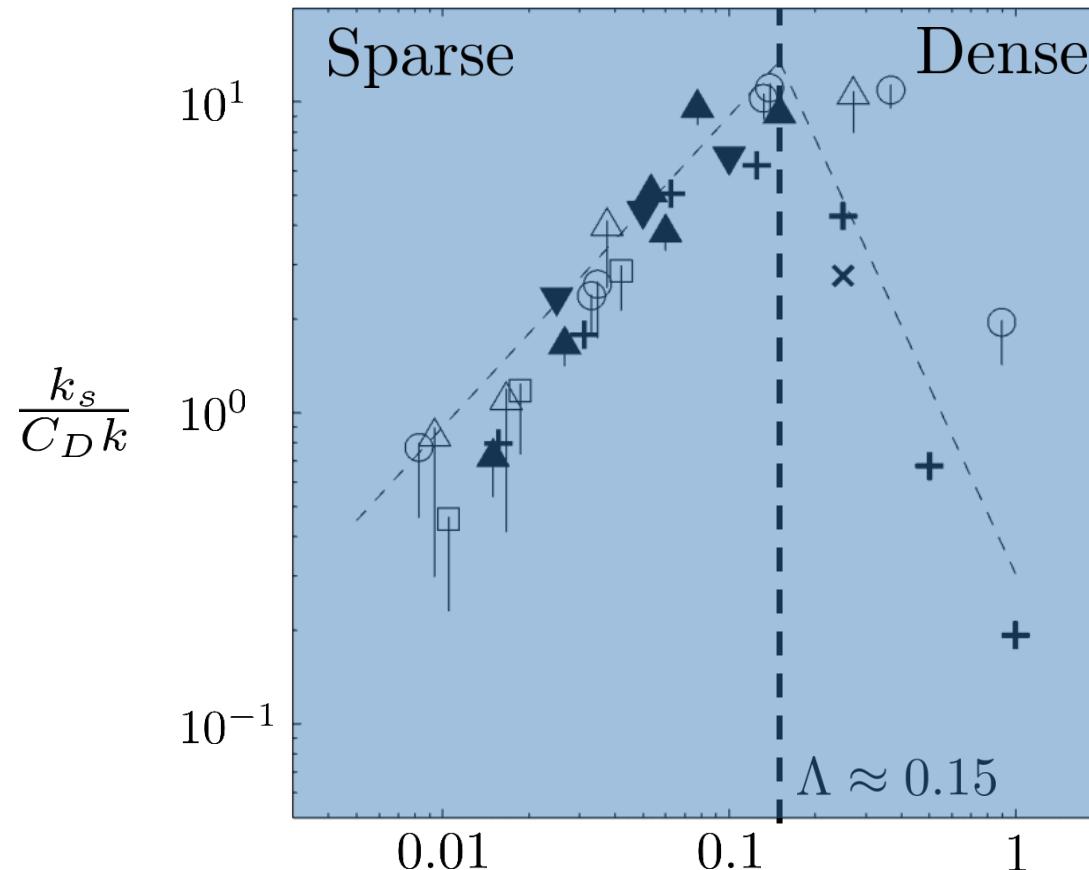
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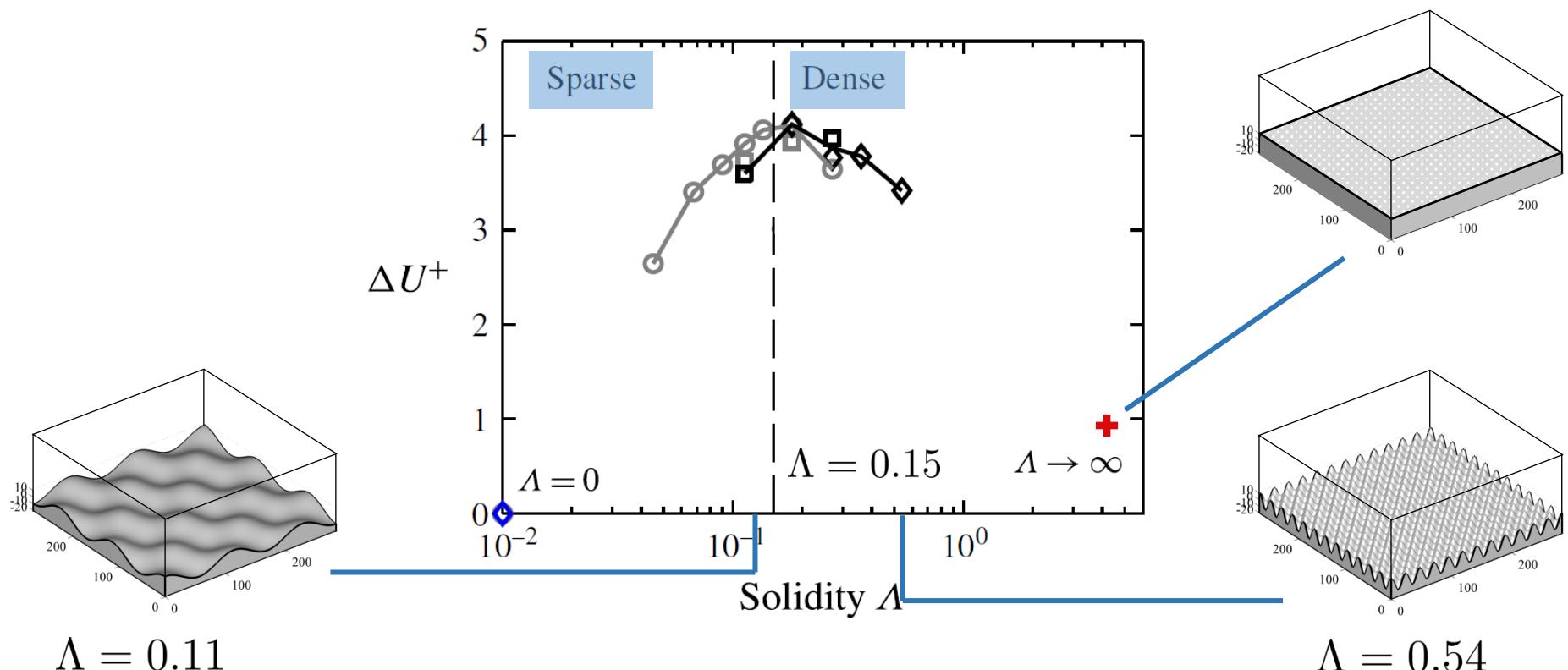
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$$\Lambda = \frac{A_f}{A_p} \quad \text{Jiménez (2004, Annu. Rev. Fluid Mech.)}$$

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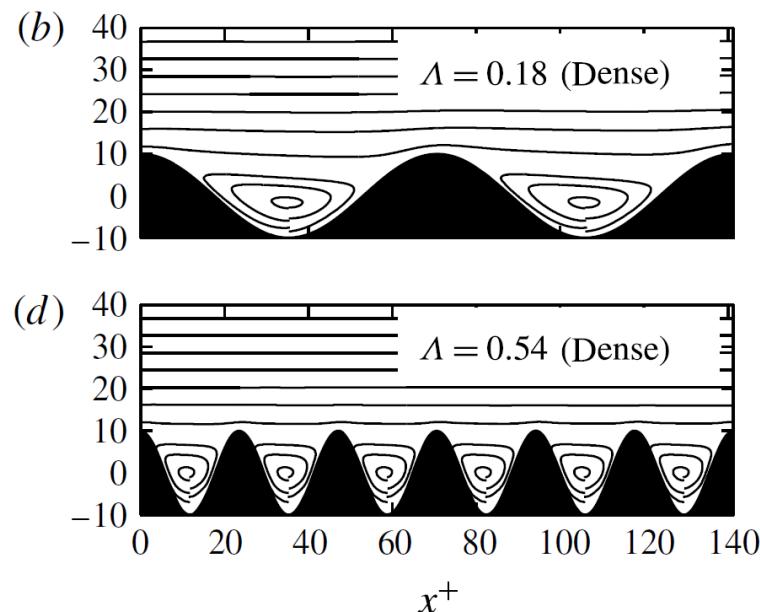
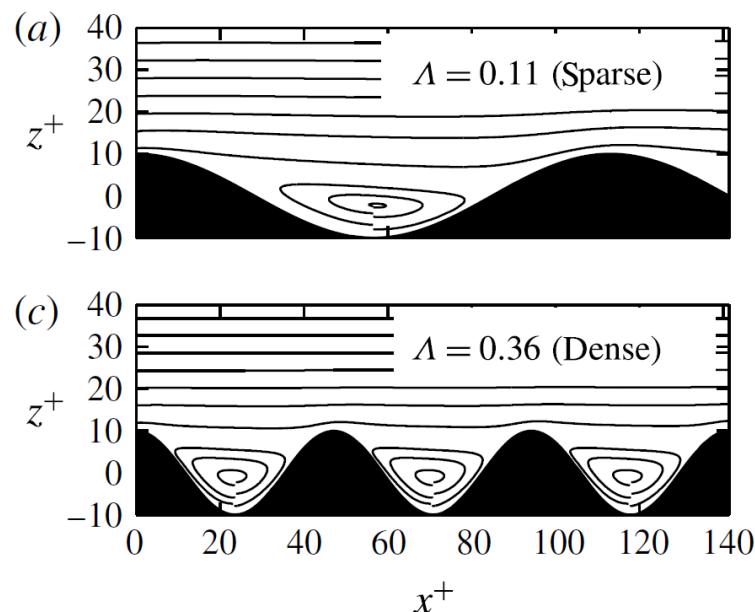


$\Lambda = 0.11$

$\Lambda = 0.54$

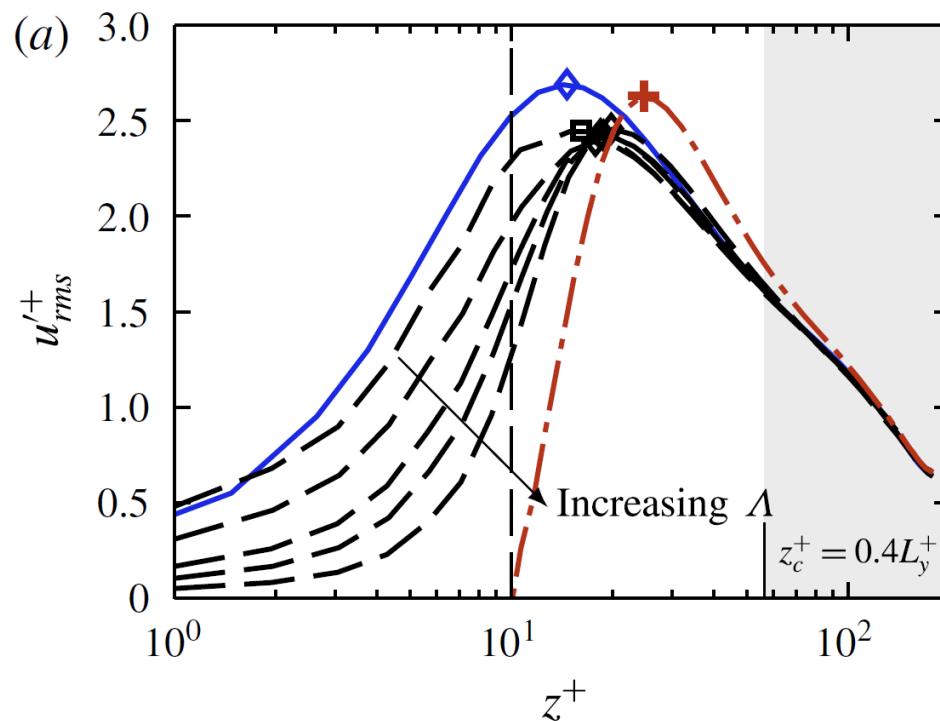
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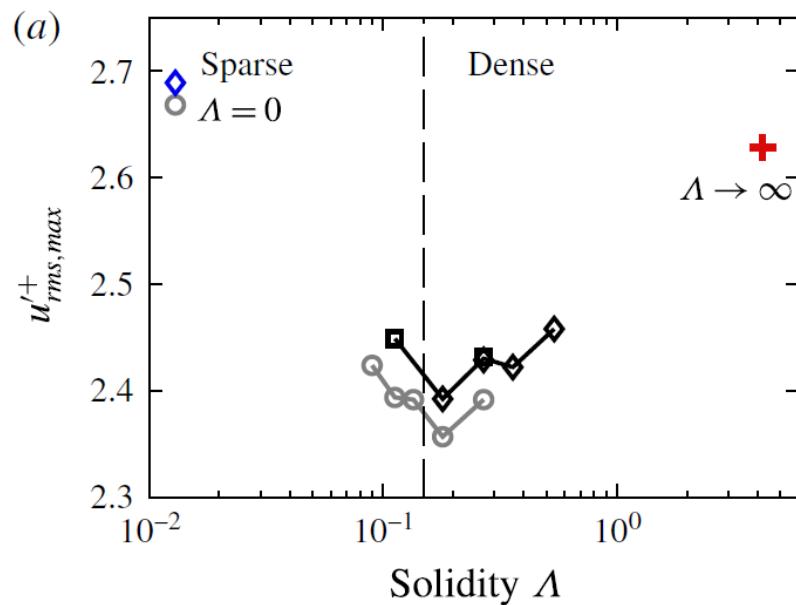
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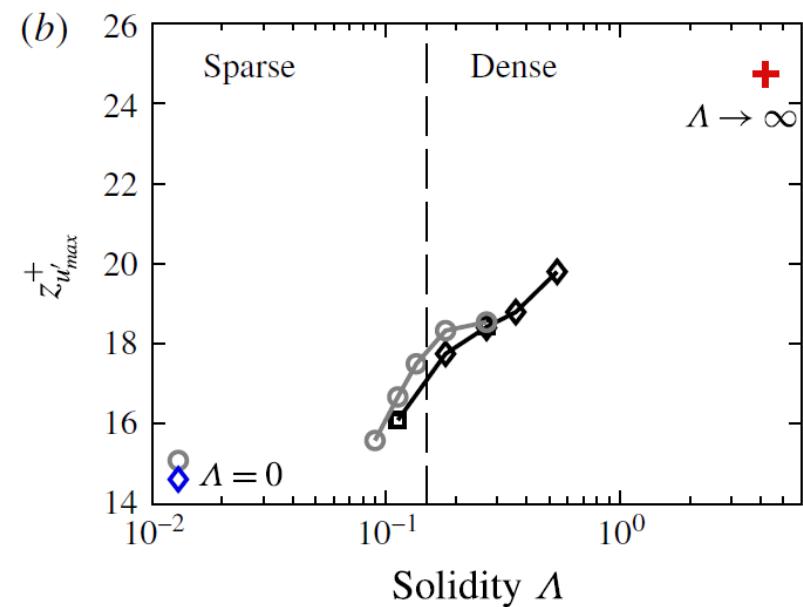
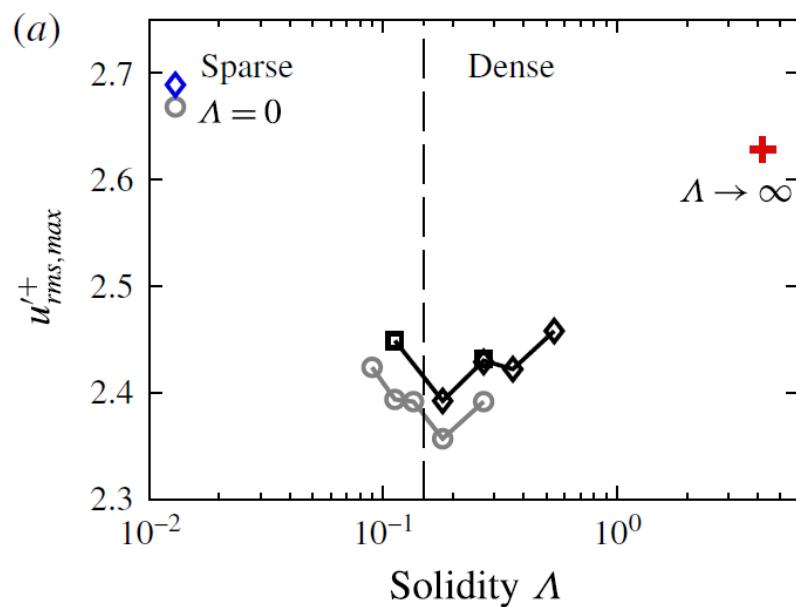
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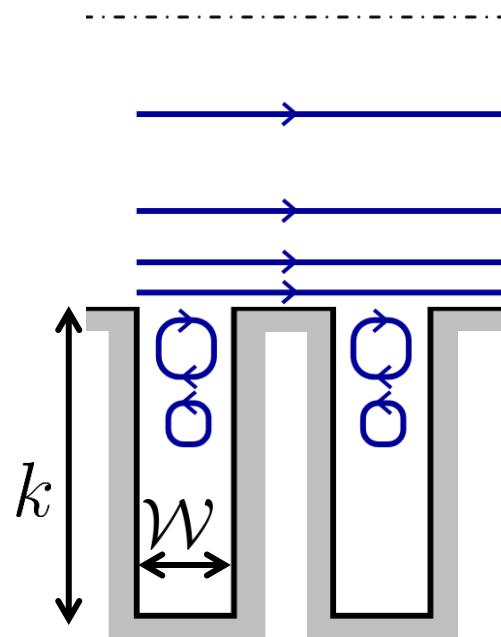
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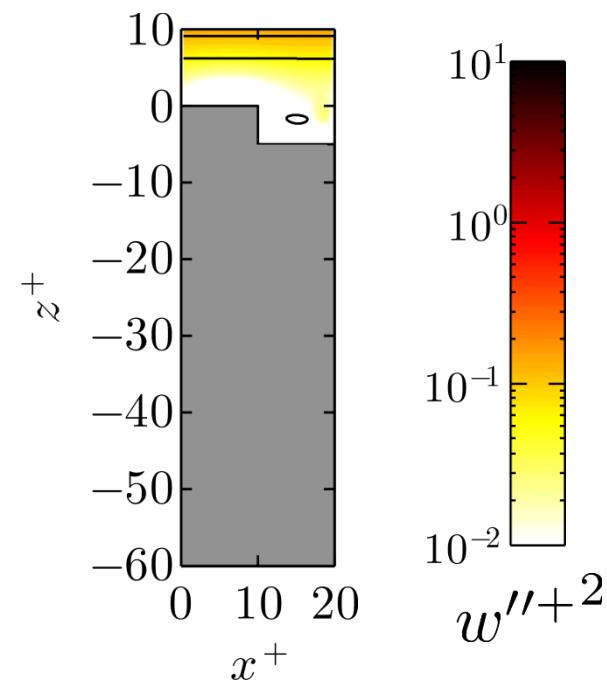
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- Use this method to investigate various rough-wall geometries
  - Square-based pyramids
  - Three-dimensional sinusoidal roughness
  - Spanwise-aligned rectangular bars ( $d$ -type roughness)



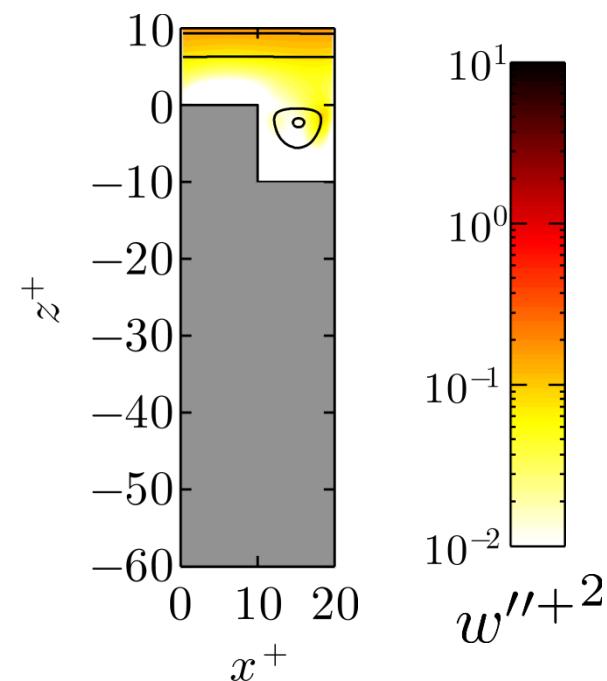
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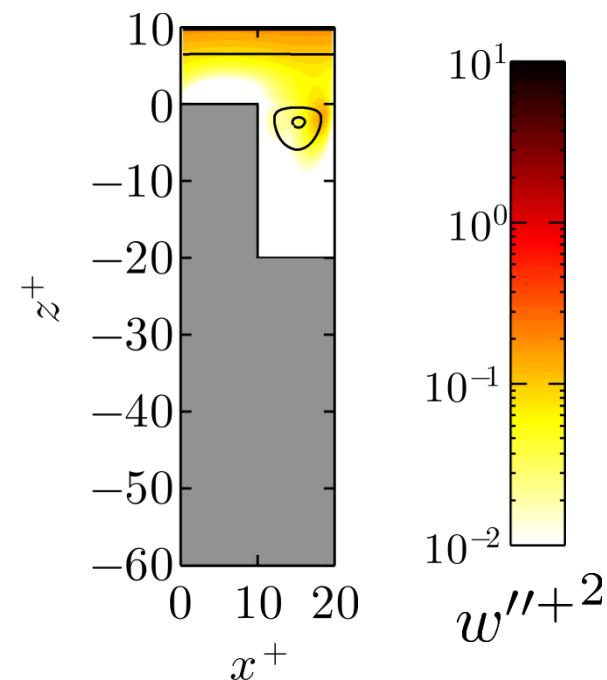
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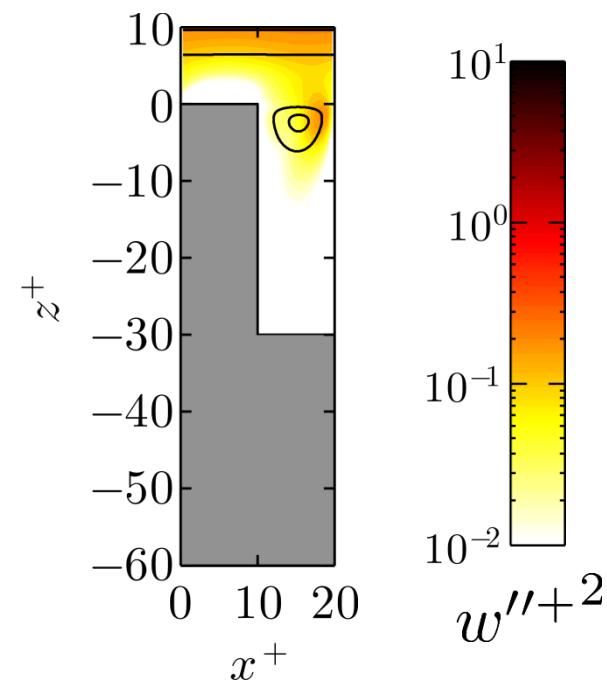
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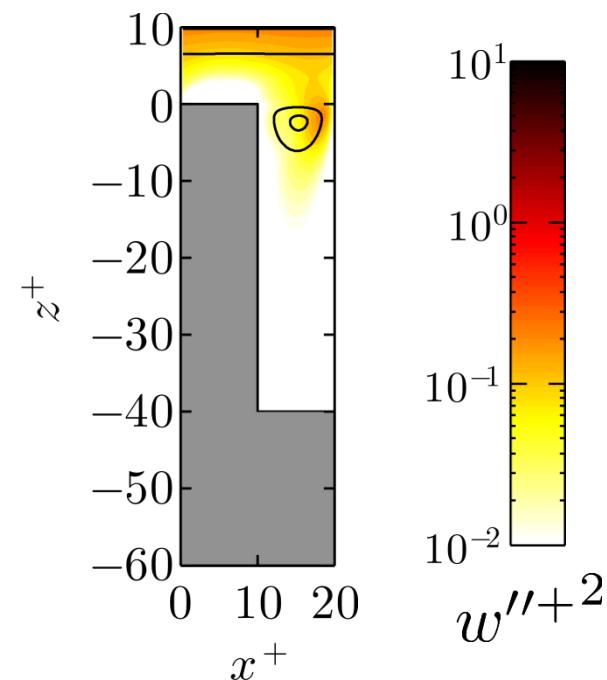
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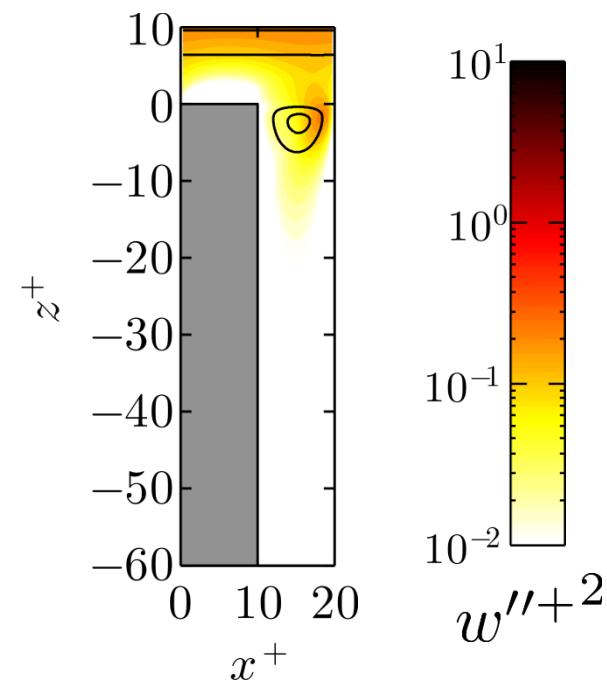
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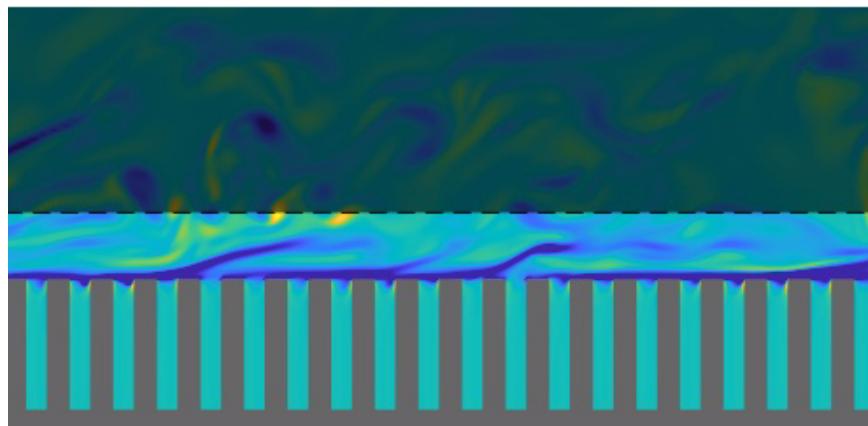
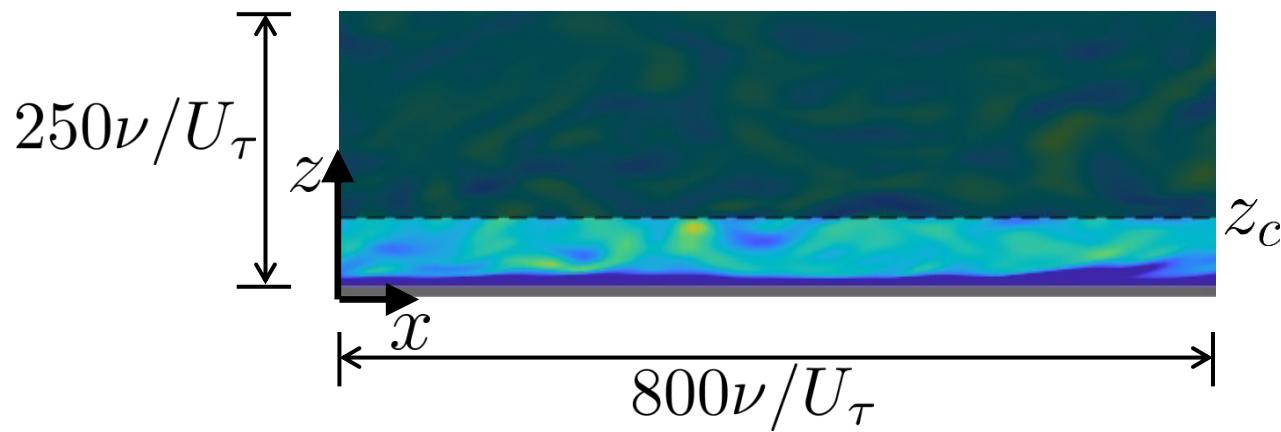
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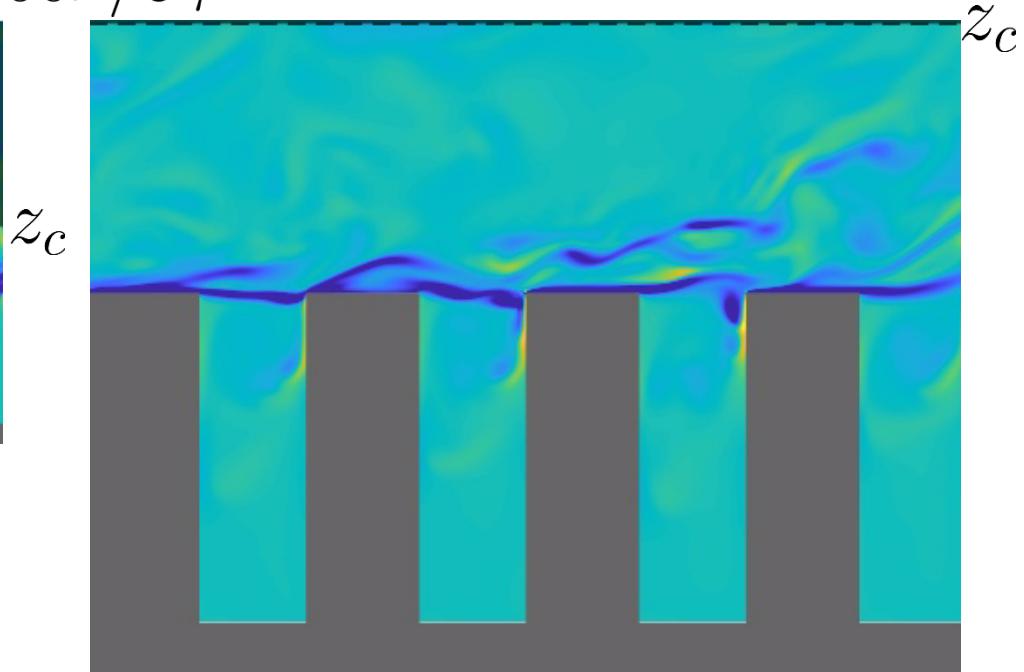


# Minimal-Span Channel

Vorticity  $\omega_y$

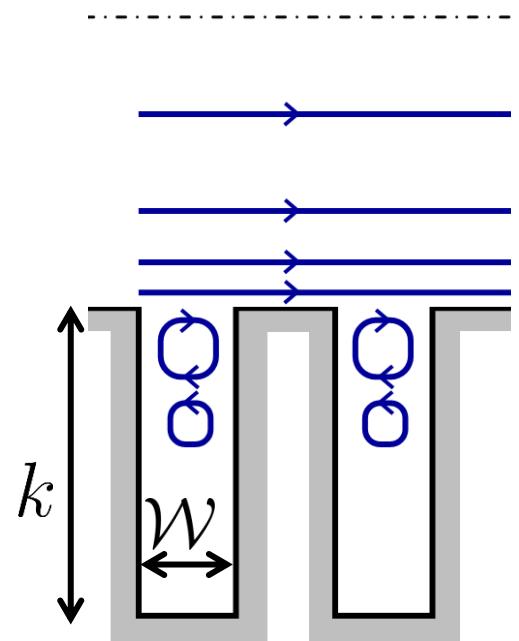
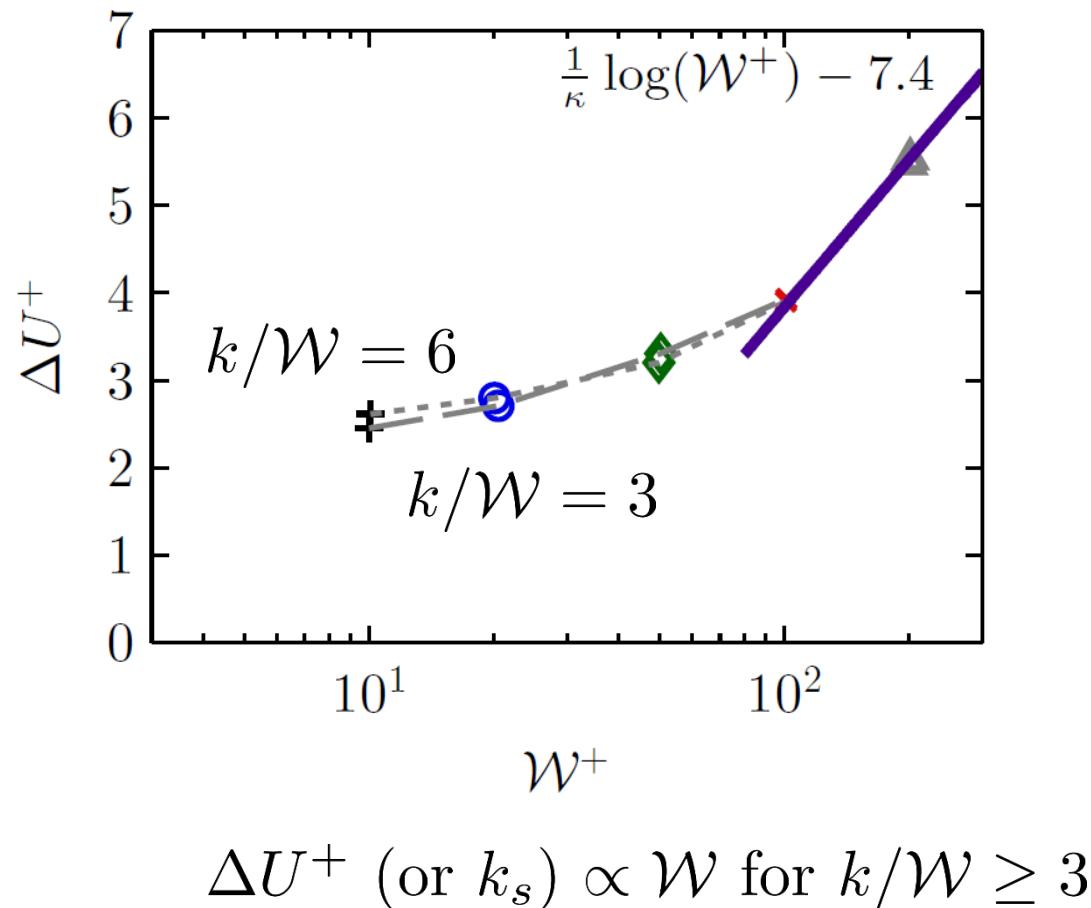


$$\mathcal{W}^+ = 20, k^+ = 120$$

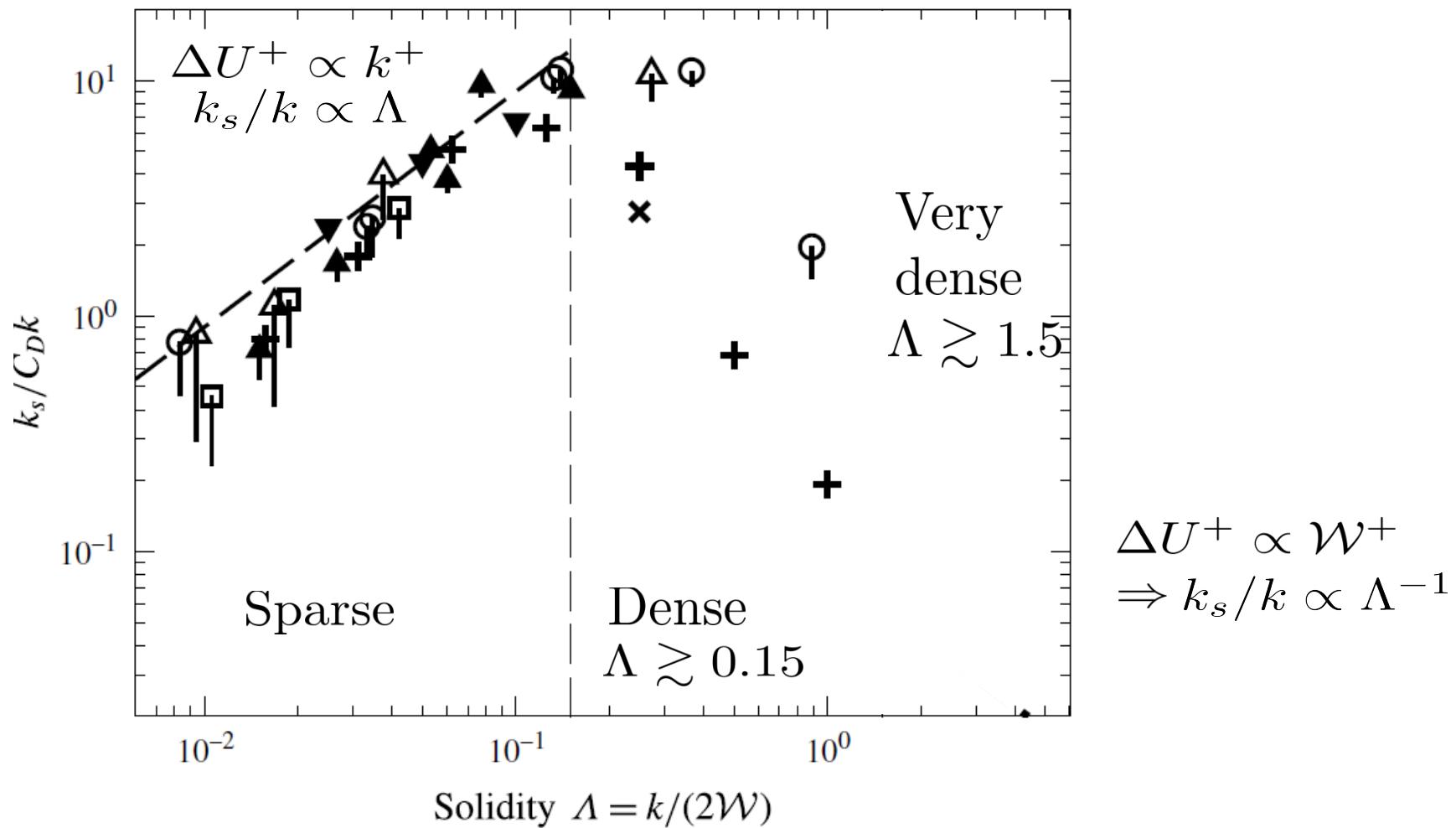


$$\mathcal{W}^+ = 100, k^+ = 300_{60}$$

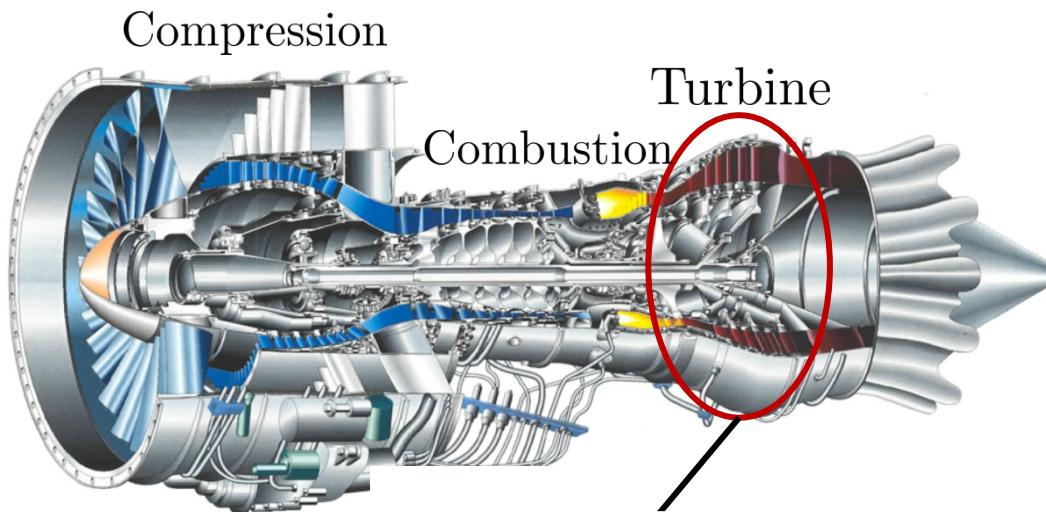
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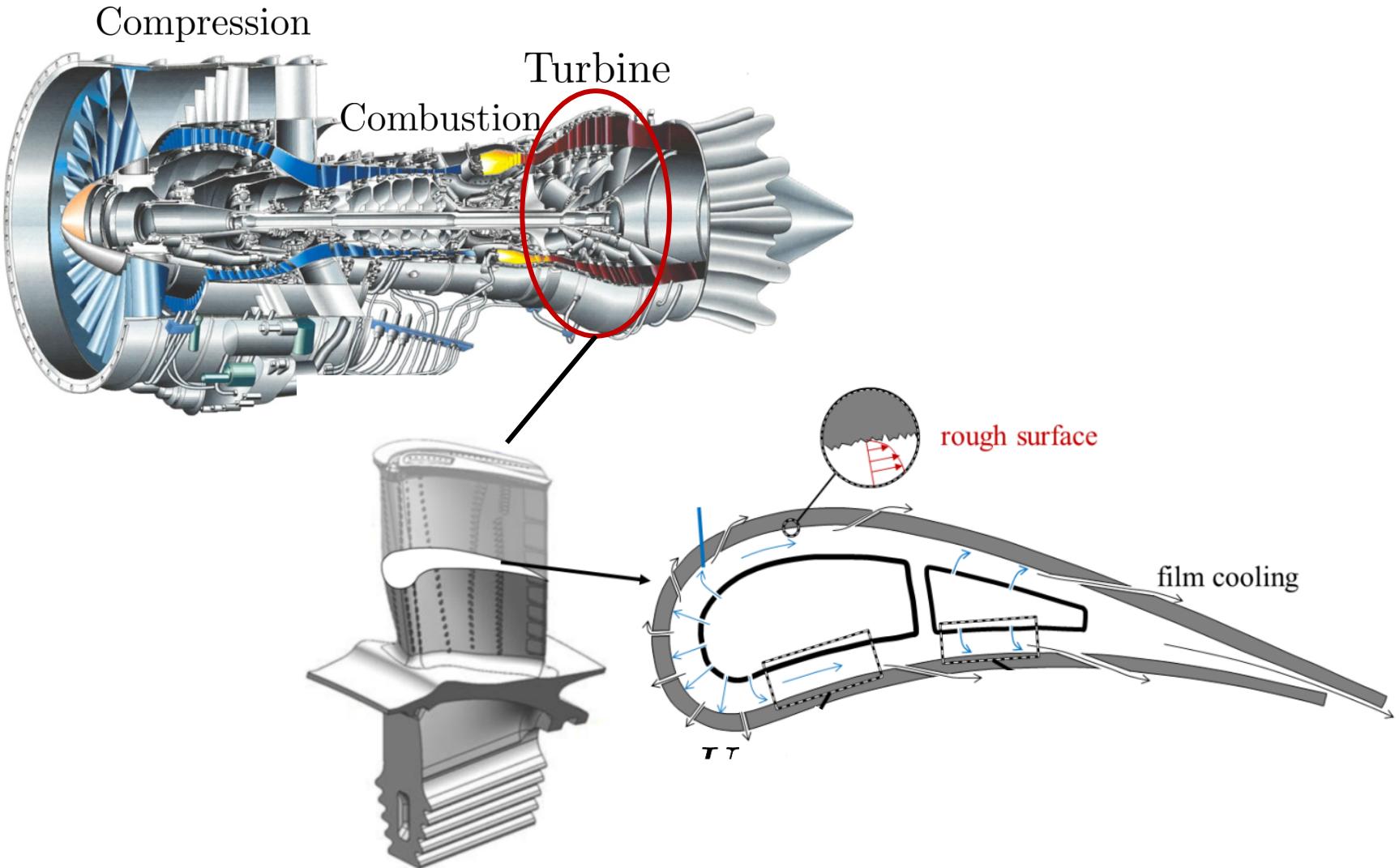
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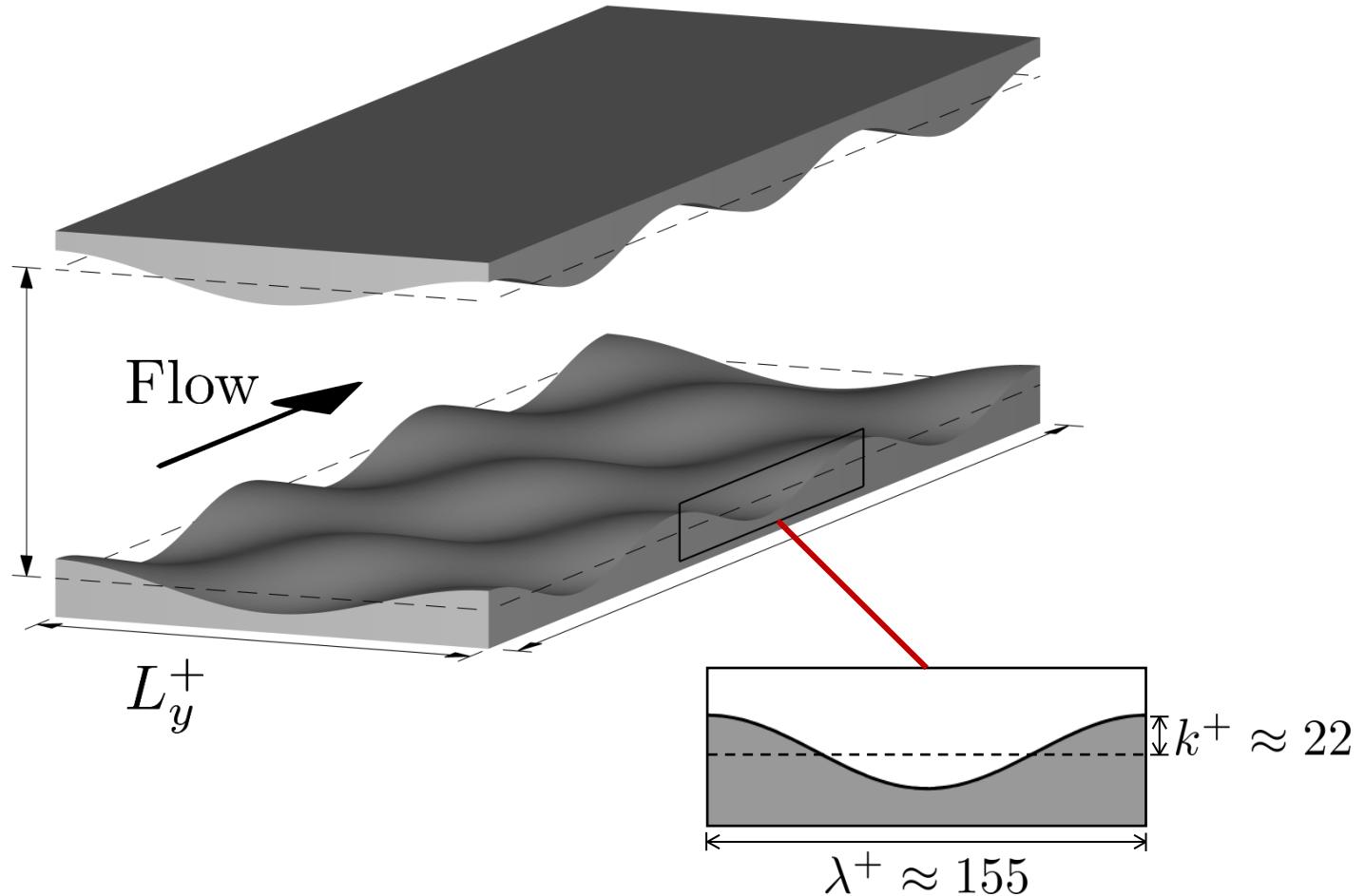
# Heat Transfer



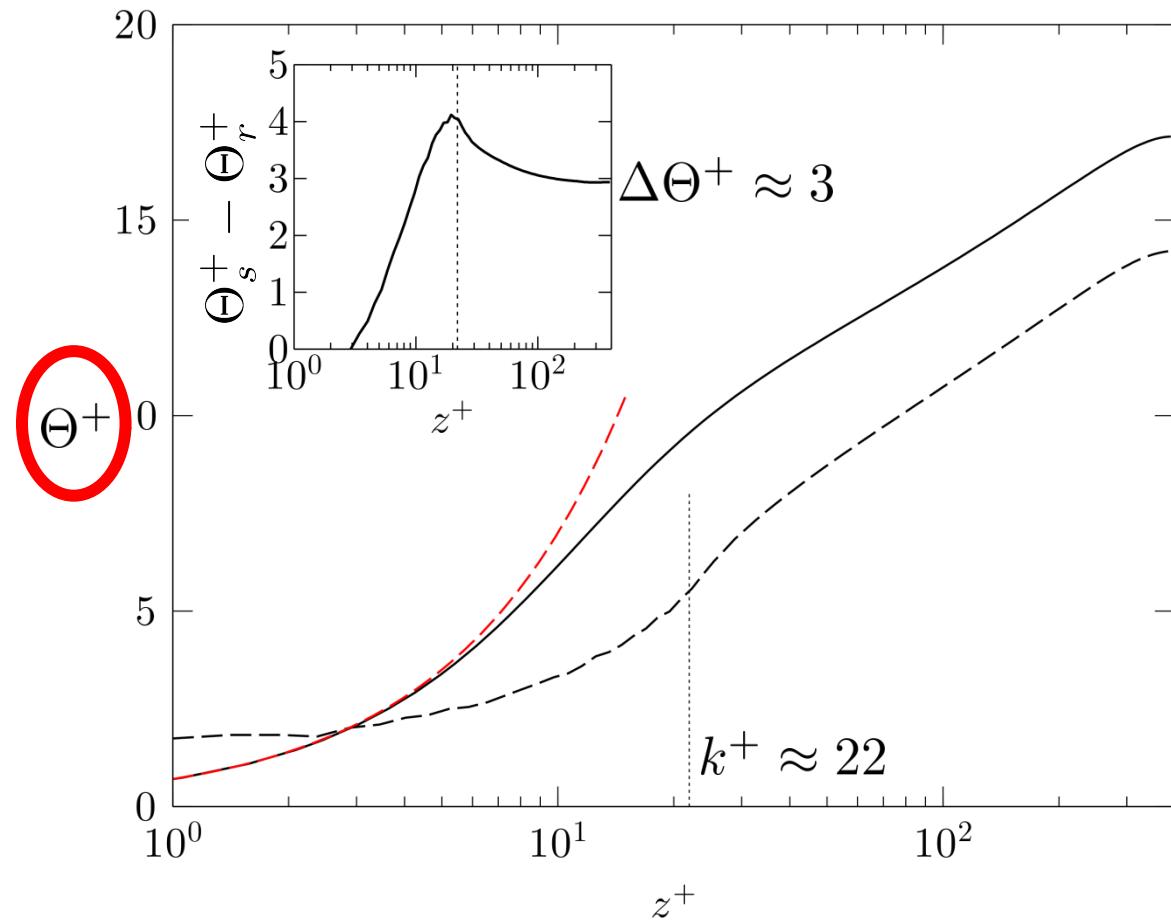
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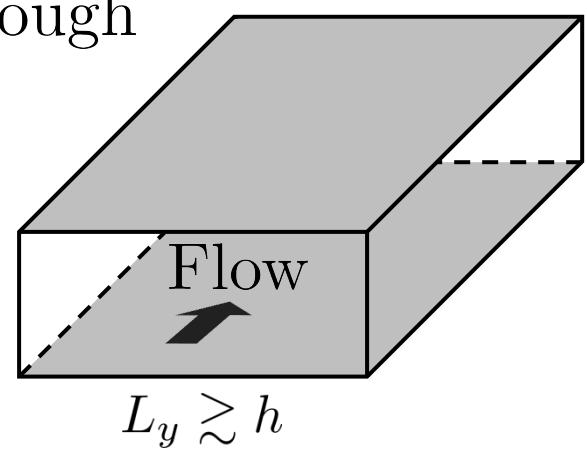
# Heat Transfer



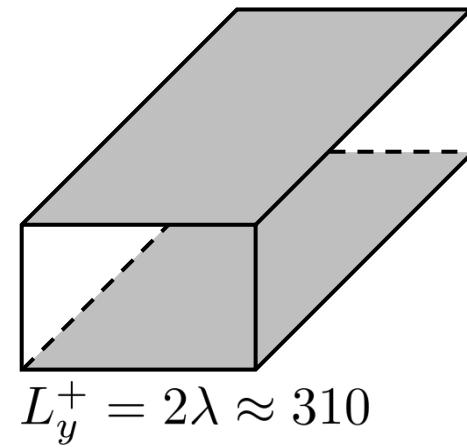
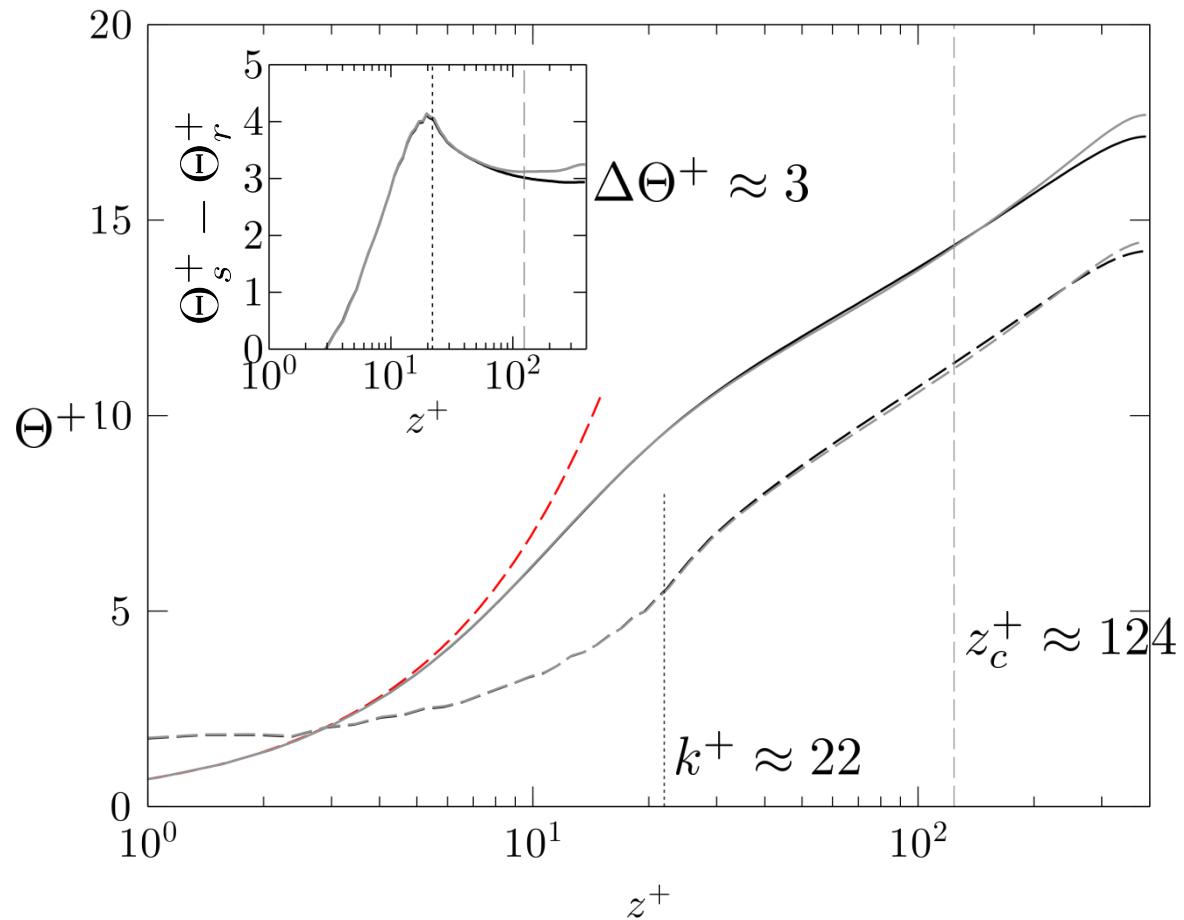
# Heat Transfer



Smooth  
Rough

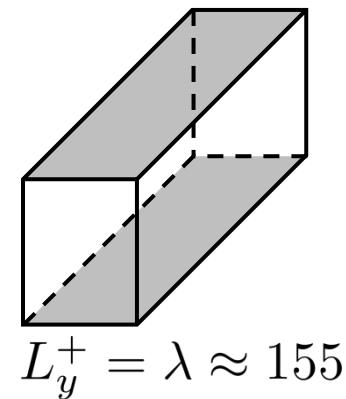
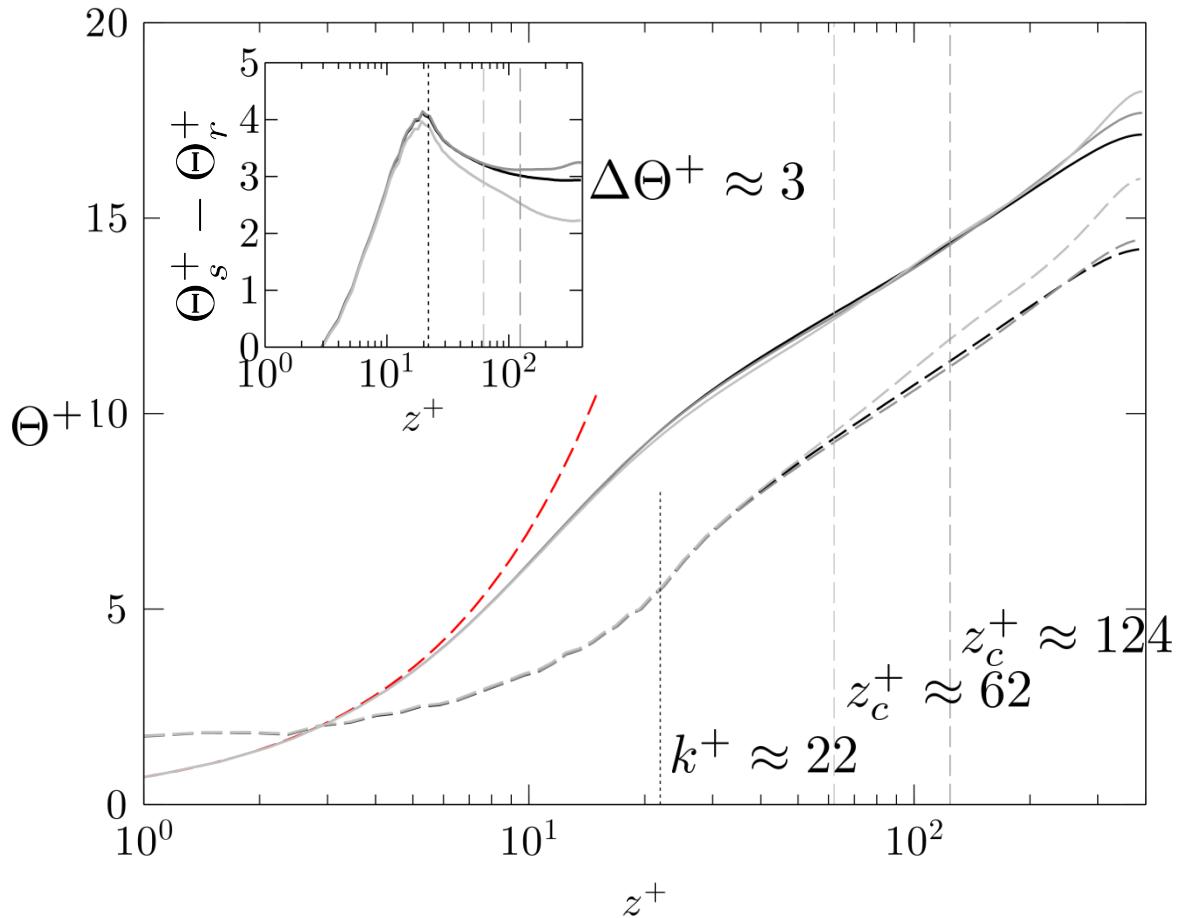


# Heat Transfer



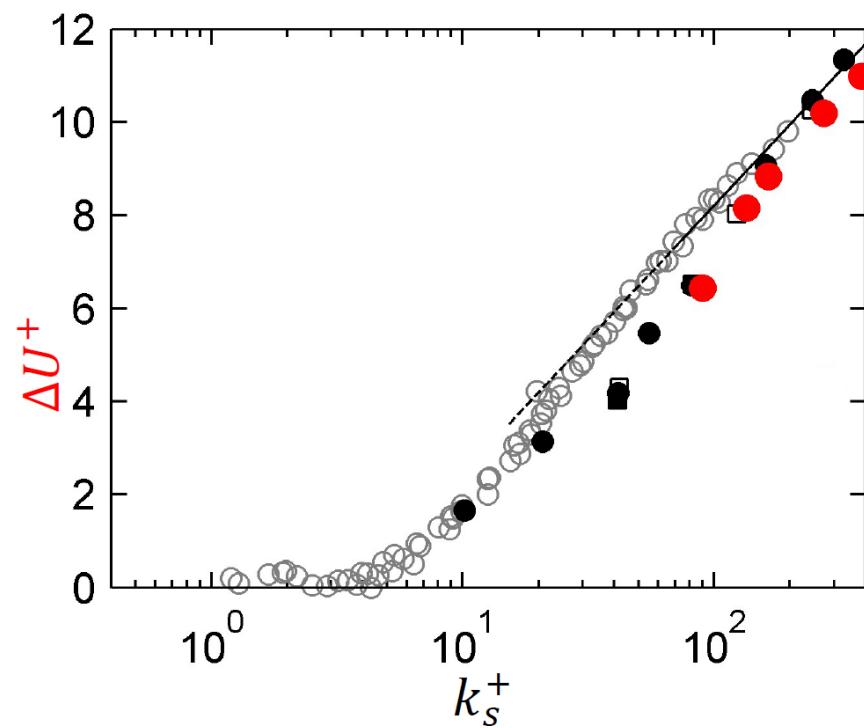
$$L_y^+ = 2\lambda \approx 310$$

# Heat Transfer

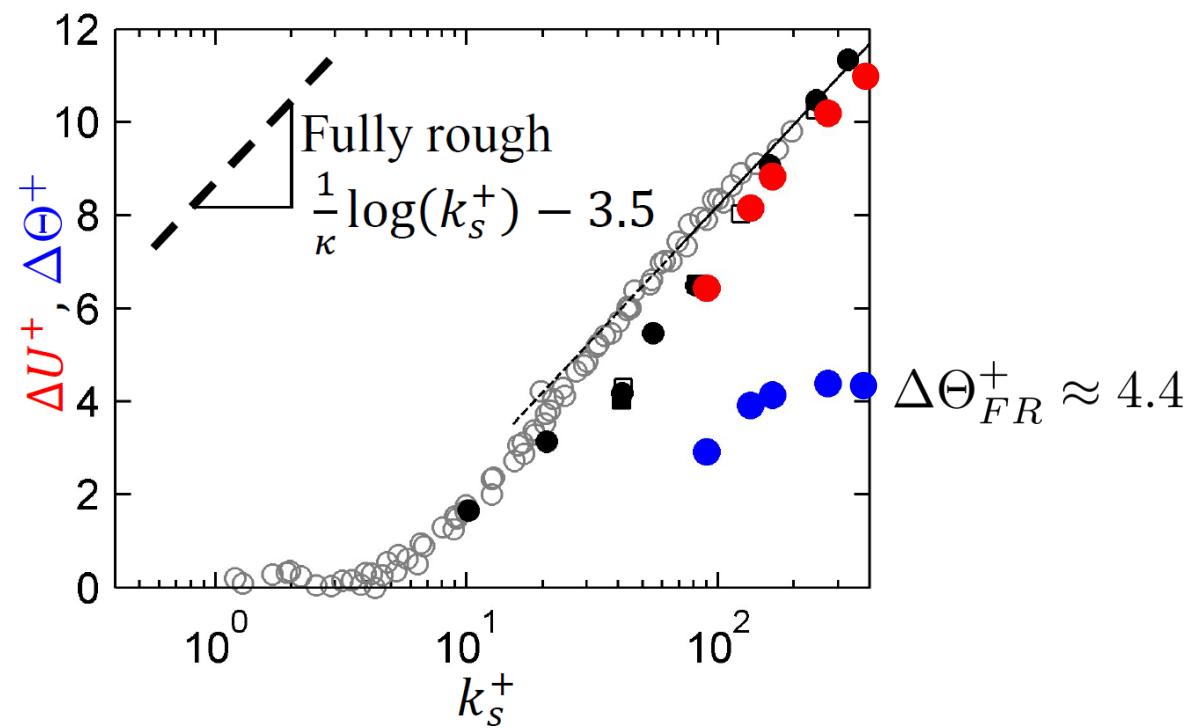


$$L_y^+ = \lambda \approx 155$$

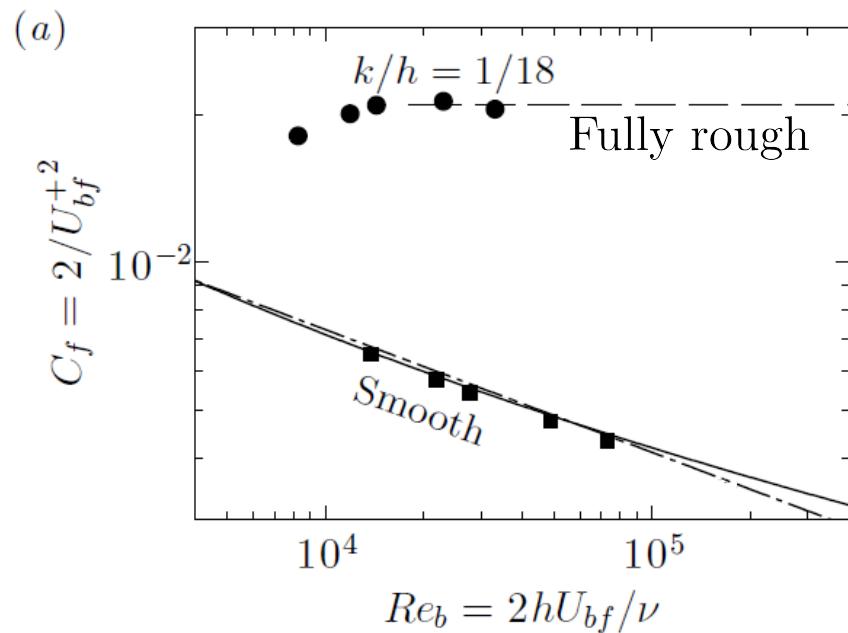
# Heat Transfer



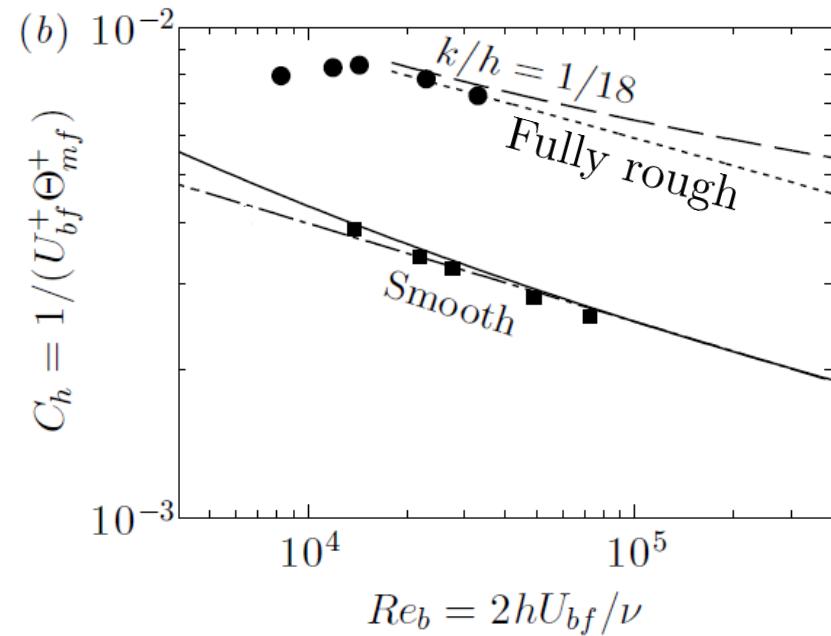
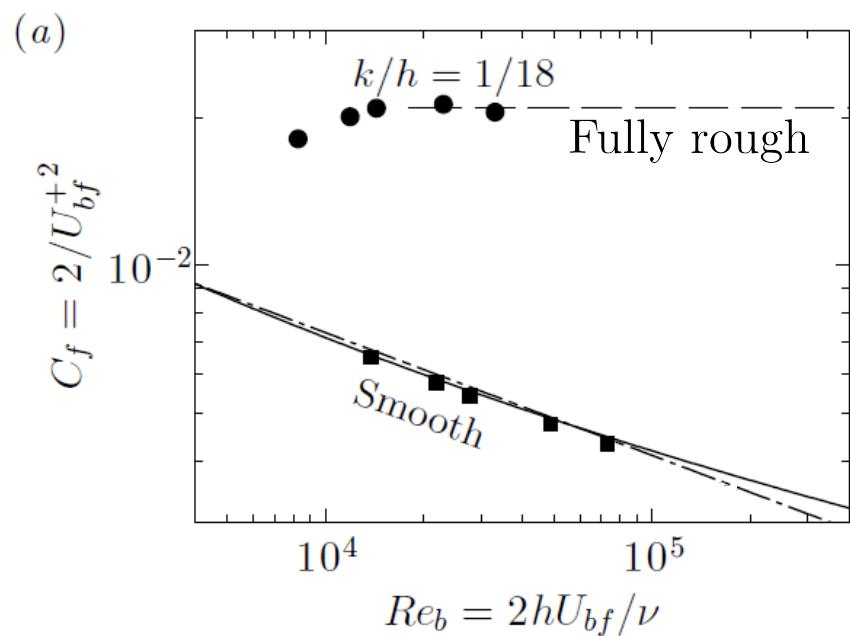
# Heat Transfer



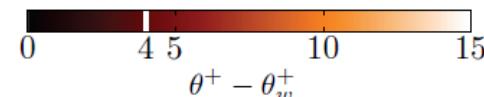
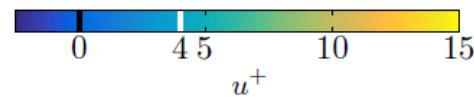
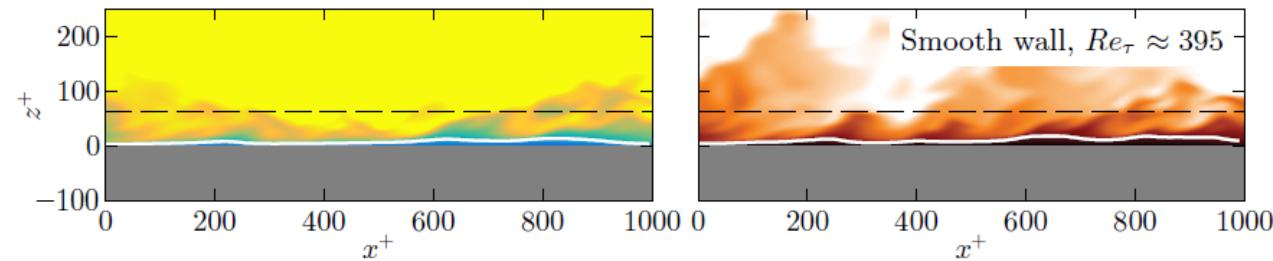
# Heat Transfer



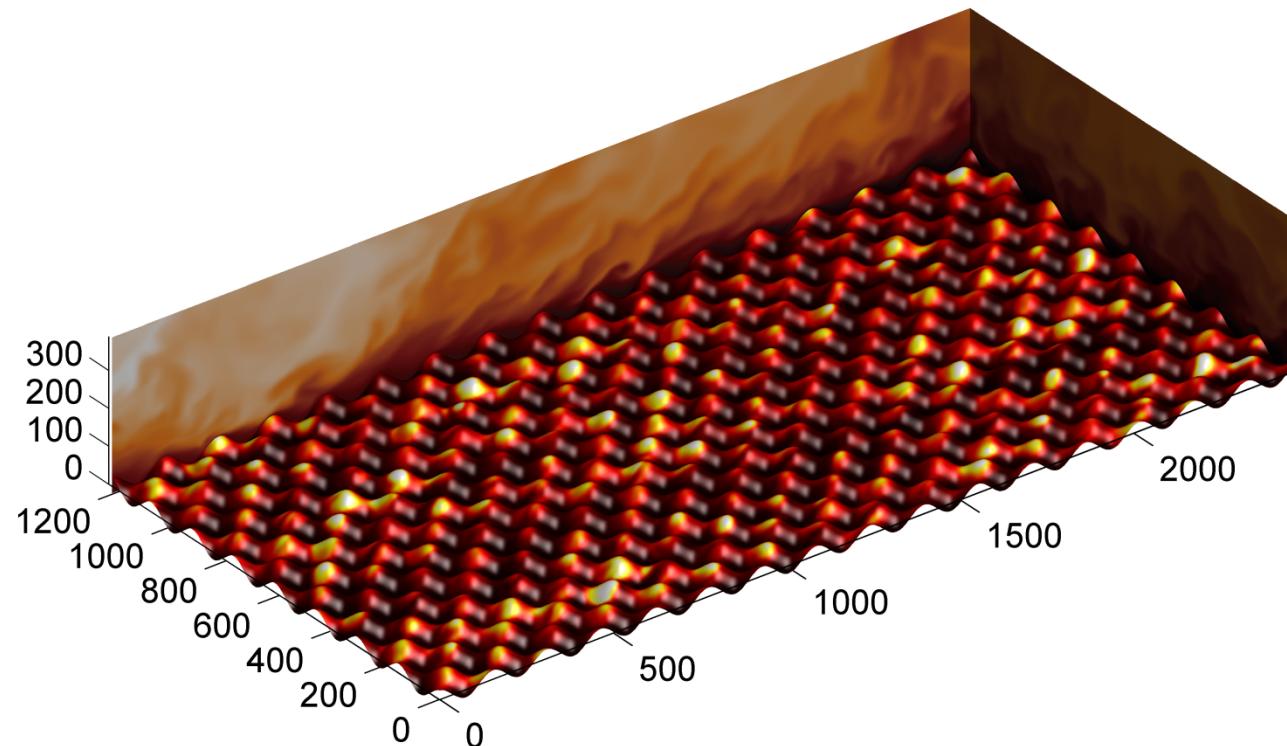
# Heat Transfer



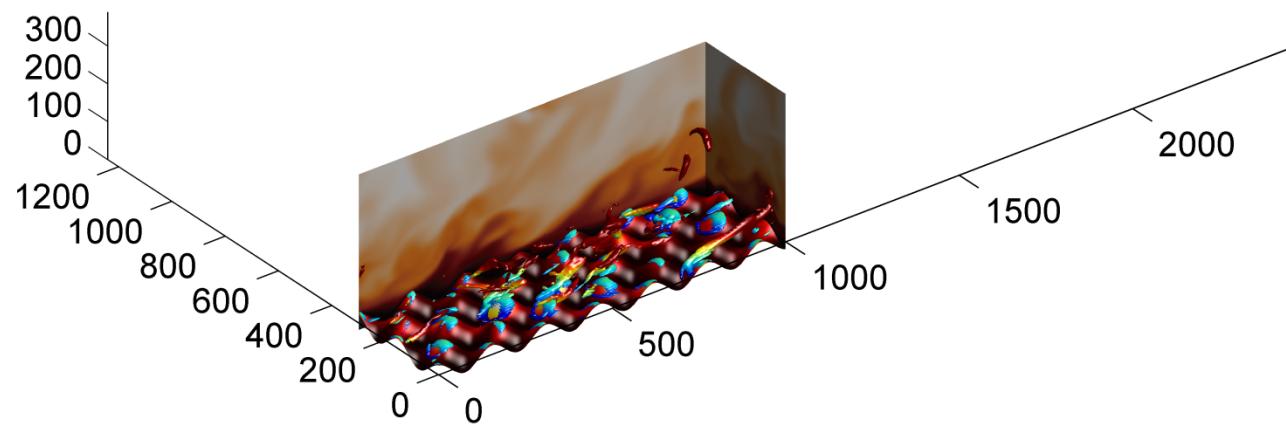
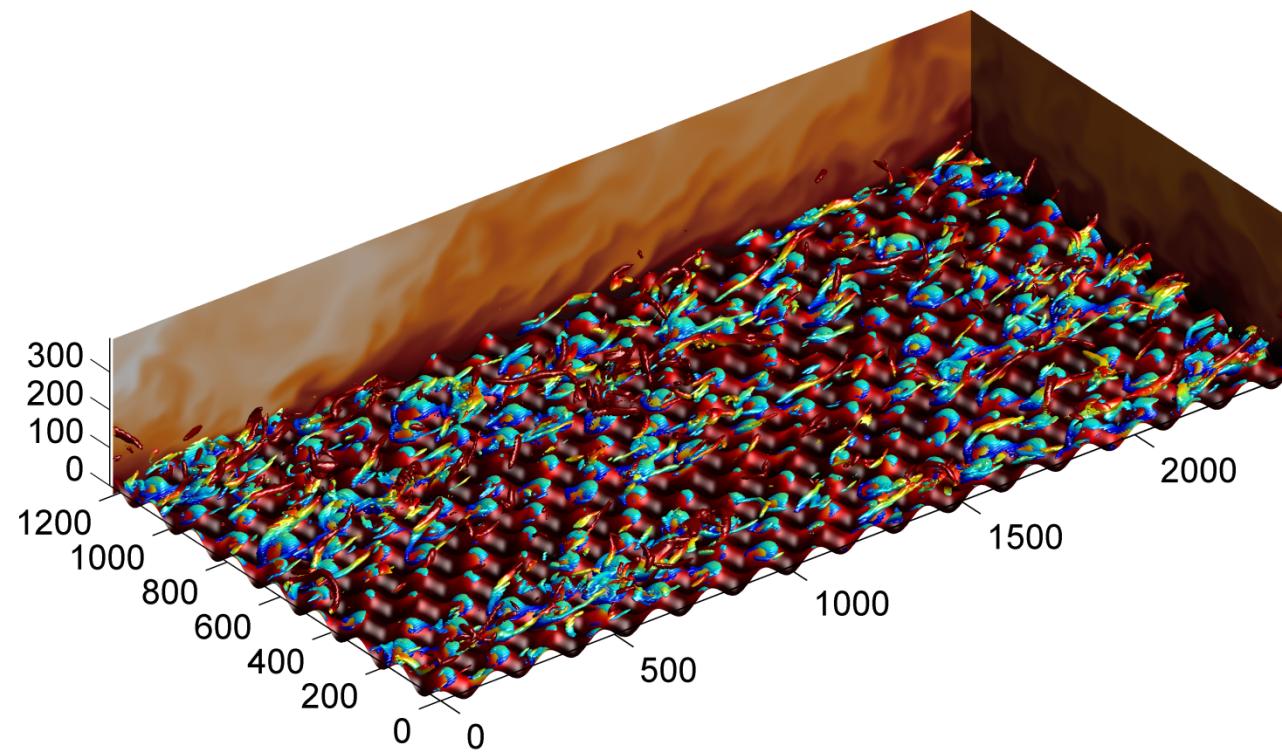
# Heat Transfer



# Heat Transfer

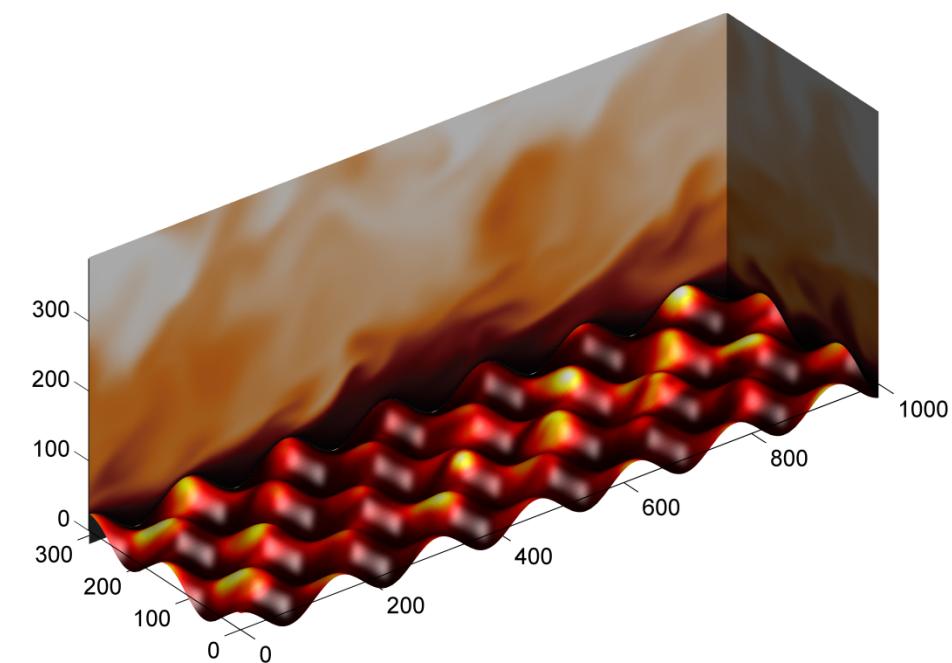


# Heat Transfer

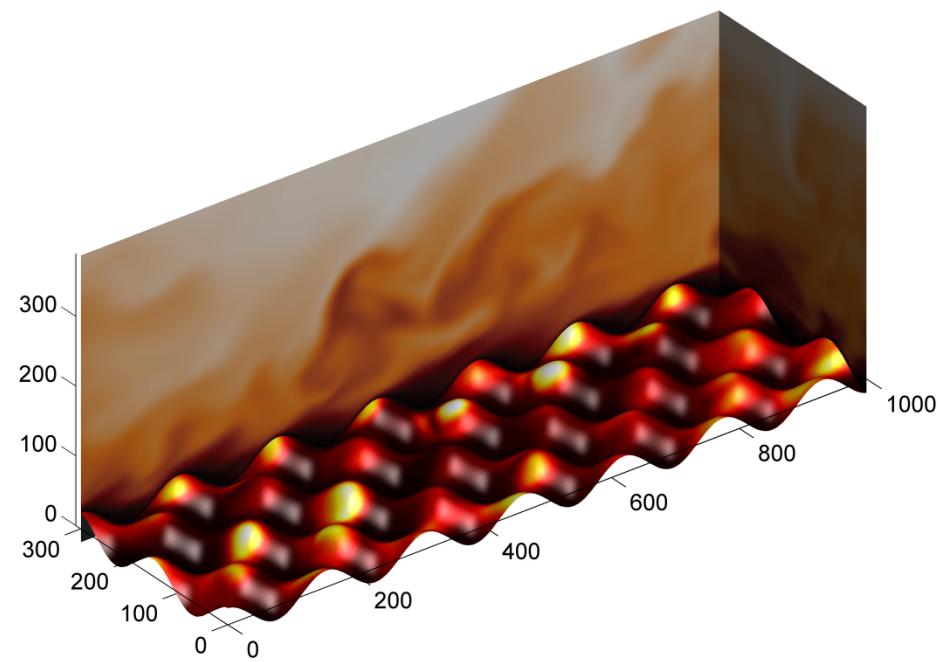


# Heat Transfer

Full span



Minimal span



# Conclusions

Rough-wall minimal-span channel

Accurately and efficiently computes  $\Delta U^+$  (or  $k_s$ )

Can also be used in forced convection to obtain  $\Delta\Theta^+$

Tool to study near-wall rough-wall physics

## References:

- MACDONALD, M., HUTCHINS, N. & CHUNG, D. 2018 Roughness effects in turbulent forced convection *J. Fluid Mech.* Under review.
- MACDONALD, M., OOI, A., GARCÍA-MAYORAL, R., HUTCHINS, N. & CHUNG, D. 2018 Direct numerical simulation of high aspect ratio spanwise-aligned bars *J. Fluid Mech.* **843**, 126–155
- MACDONALD, M., CHUNG, D., HUTCHINS, N., CHAN, L., OOI, A. & GARCÍA-MAYORAL, R. 2017 The minimal-span channel for rough-wall turbulent flows. *J. Fluid Mech.* **816**, 5–42
- MACDONALD, M., CHAN, L., CHUNG, D., HUTCHINS, N. & OOI, A. 2016 Turbulent flow over transitionally rough surfaces with varying roughness densities. *J. Fluid Mech.* **804**, 130–161
- CHUNG, D., CHAN, L., MACDONALD, M., HUTCHINS, N. & OOI, A. 2015 A fast and direct numerical simulation method for characterising hydraulic roughness. *J. Fluid Mech.* **773**, 418–431

# Minimal-Span Channel

1. Determine  $k^+$  and  $\lambda_{r,x}$ ,  $\lambda_{r,y}$  of roughness

2. Determine  $L_y^+$ , and hence  $z_c^+ = 0.4L_y^+$   
$$L_y^+ \geq \max(100, k^+/0.4, \lambda_{r,y})$$

3. Determine  $L_x^+$

$$L_x^+ > \max(3L_y^+, 1000, \lambda_{r,x})$$

4. Select desired accuracy in  $\Delta U^+$

$$\Delta U^+ \pm \zeta$$

5. Determine  $C^\star = f(z_c^+, \zeta)$  and hence  $T_{sim}$

# Minimal-Span Channel

Cost and Convergence

Full-span,  $T_{sim}U_\tau/h \approx 10$

# Minimal-Span Channel

Cost and Convergence

Minimal-span

95% confidence interval,  $\Delta U^+ \pm 2.77\epsilon^+$

# Minimal-Span Channel

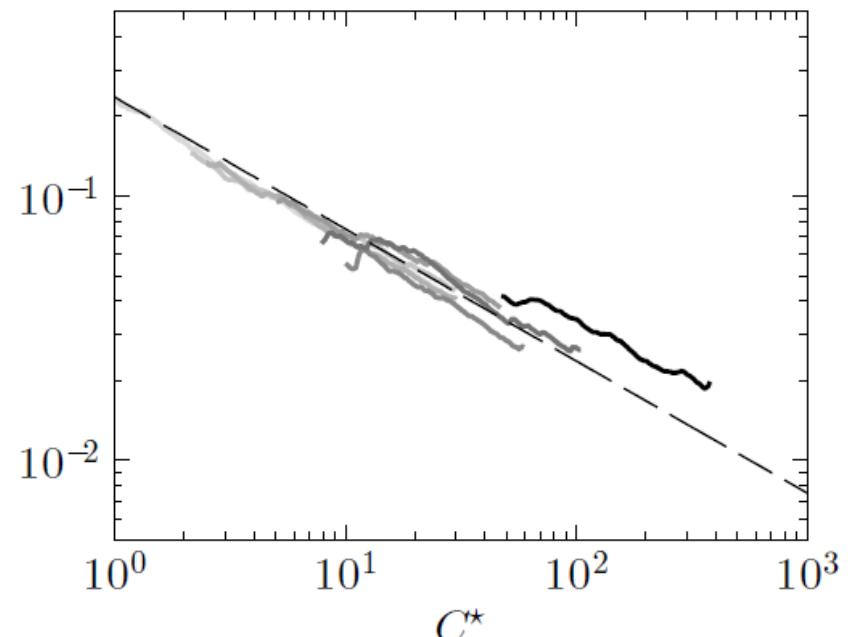
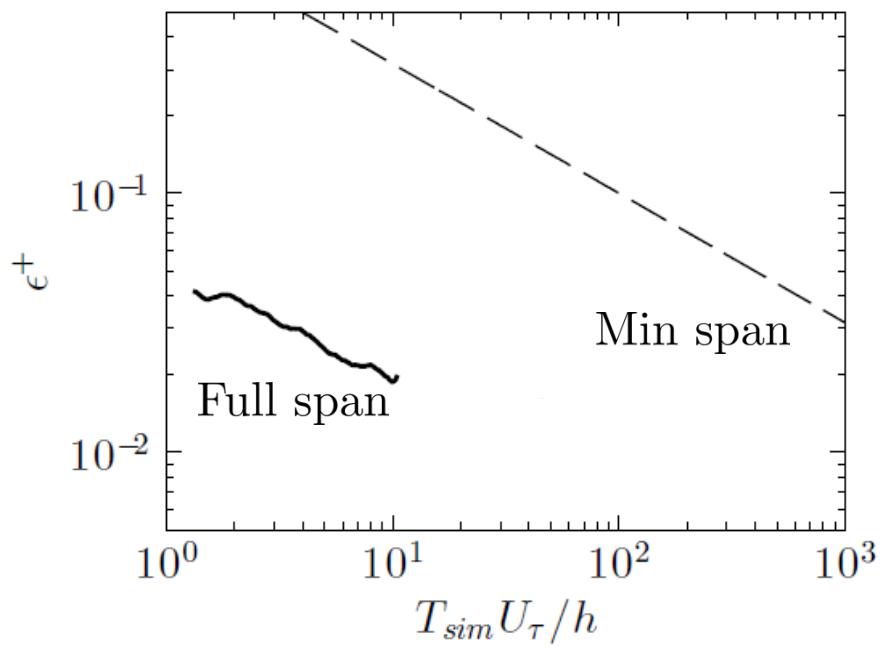
## Cost and Convergence

Minimal-span

95% confidence interval,  $\Delta U^+ \pm 2.77\epsilon^+ = \Delta U^+ \pm \zeta$

$\epsilon^+$  = standard error of the velocity signal at  $z_c$

$$= K(C^*)^{-1/2}$$



User-set target  
↓  
Number of eddy lifespans  
during the simulation